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MAY-JUNE 1943

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THE JOURNAL OF GEOLOGY

May-June 1943

SOME ALTERED PALAGONITE TUFFS FROM JAMAICA AND THE ORIGIN AND HISTORY OF THEIR CHLORITES[1]

FRANK RAW
University of Birmingham, England

With a section on the geologic relationships by

C. A. MATLEY
Leamington, England

ABSTRACT

Slightly and moderately deformed palagonitic rocks from Jamaica suggest the destiny of palagonite. The principal rock described indicates its origin in sideromelane tuff, gives evidence of a palagonite-tuff stage, and displays in detail its mode of deformation. Sideromelane is inherently unstable; and palagonite, the product of the action of water upon it, is essentially chlorite. But palagonitization is slow, and, before it is much advanced, the rock spaces have usually been filled with low-grade chlorite followed by zeolite. The deposition of chlorite is often in two stages, which may differ entirely in orientation. Deformation, facilitated by the low resistance, raises the grade of both these chlorites; and chlorite schists and chlorite and albite schists, it is suggested, largely result from the dynamometamorphism of palagonite tuffs.

INTRODUCTION

Among twelve specimens, selected by Dr. C. A. Matley from a collection made by him when surveying in Jamaica in the spring of 1939, and which, accompanied by microsections, were submitted to the author, there was found a volcanic ash, which is in two respects of quite exceptional interest. First, its mineral character is of a type hitherto apparently unrecorded, and, second, its metamorphism, which is very clearly displayed, exhibits distinctly novel features. Study of the rock led to comparisons with palagonite tuffs, chiefly from Iceland, and to a detailed study of these. This again led to new views as to the nature, origin, and destinies of palagonite tuffs in general.

Subsequently, among a suite of rocks also collected by Dr. Matley in the same year but in another district, four other comparable but very different pyroclastic rocks were discovered, confirming the conclusions reached from a study of the first. The present paper embraces descriptions of these rocks and a discussion of the mineralogical and petrological conclusions arising therefrom. Dr. Matley has kindly furnished the following statement of their geologic relationships.

[1] Part of a paper read before the Geological Society of London on May 21, 1941, entitled "On a Remarkable Volcanic Tuff from Near Kingston, Jamaica, and Its Bearings on the Nature, Origin, and Destiny of Palagonite" ([Abstr.], *Proc. Geol. Soc. London*, No. 1379 [June, 1941] pp. 64–70), together with descriptions of other Jamaican palagonitic rocks supplementing and confirming the conclusions already reached.

GEOLOGIC RELATIONSHIPS

Apart from pre-Cretaceous volcanic materials present in the basal complex, the rocks of Jamaica give evidence of three periods of vulcanicity.

1. The Upper Cretaceous sediments with their Rudist limestones are associated with great thicknesses of lavas and tuffs of an andesitic type. They are usually red from hematization. It is in this series that the second discovery of palagonitic rocks was made.

2. Highly vesicular basic (and perhaps spilitic) lavas associated with basic tuffs (often dark green) are found in the country east of Kingston, especially around Halberstadt, where they are present in some abundance. Some of the flows have a marked pillow structure. They were laid down in water and are definitely of Eocene age, as shown by the few marine fossils in the associated shallow-water sediments. The horizon is probably Lower Eocene and certainly not younger than Middle Eocene. Farther north, in the folded conglomerate, sandstone, and shale country on both sides of the Kingston—Newcastle—Buff Bay Road, is a number of small outcrops of a thin series of basic lavas and tuffs, which are probably all on one Eocene horizon and seem to be an extension of the much thicker volcanic group at Halberstadt. They are intercalated in the upper part of the Wagwater (Purple Conglomerate) group, where it passes up into the brown-weathering or "Carbonaceous Shale" group of Sawkins. Like those of Halberstadt, these lavas are vesicular, and the spheroidal masses suggest pillow structure. The first specimen under description came from this group. In the same area are a few basic sills and dikes, some of which contain olivine. The great Newcastle sill of feldspar-porphyry is intruded at a level not far removed from the volcanic horizon.

3. The only locality where the youngest volcanic rocks of Jamaica occur is at Low Layton on the north coast between Buff Bay and Port Antonio. Here vesicular basic lavas with fine pillow structure are found associated with the Montpelier or chalky facies of the White Limestone, and globeriginae can be found lying in the vesicles at the top of the flows, which are therefore submarine. This episode is of Upper Eocene or Lower Oligocene date.

As stated above, the first tuff under description comes from a thin volcanic group of Lower, or possibly Middle, Eocene age found as small outcrops in the anticlines and synclines of folded sedimentary rocks. The group consists of two or three lavas, rarely exceeding 10 feet thick; and tuffs are relatively uncommon. The specimen was obtained from the side of the main road from Kingston to Buff Bay on the northern slope of the main ridge, two miles beyond Hardwar Gap and a quarter of a mile beyond the twenty-third milepost, in the neighborhood of Limerick Mount. A lava was associated with it.

This area was involved in the Tertiary orogenesis of Jamaica. The region is highly folded, and there are important thrusts, usually high-angled, with zones of sheared rocks, some in the condition of mylonites. But otherwise there is very little dynamic metamorphism.

The other palagonitic rocks here described belong to the volcanic series of Upper Cretaceous age. They come from south of Guy's Hill between the twentieth and twenty-third mileposts of the road running north from Spanish Town.

THE TUFF FROM NEAR NEWCASTLE JAMAICA

KP 312 (microsections KP 312 *a*, *b*, and *c*) is a specimen from near Limerick Mountain, Newcastle, Jamaica, on the Buff Bay Road, $23\frac{1}{4}$ miles from Kingston. The geological horizon is the top of the Wagwater (Purple Conglomerate) group, probably Lower Eocene. Dr. Matley labeled the rock "sheared spilitic tuff."

The hand specimen by its distribution of green, white, and black suggests a gabbro greatly altered and sheared. It is all softer than a knife. It looks like a mixture of saussurite, chlorite, and black iron ore; but microscopic study at once removes this impression.

MICROSCOPIC CHARACTERS

Three microsections of the rock were made. The first section proved to be oblique to the shear structure; and, since difficulties arose in its interpretation, another section was cut at right angles to the surfaces of shear and along the direction of elongation, thus containing at the same time the directions of greatest elongation and of greatest contraction. Subsequently, for confirmation of conclusions and for more efficient service with the Dollar micrometer a third section was cut normal to the direction of elongation.

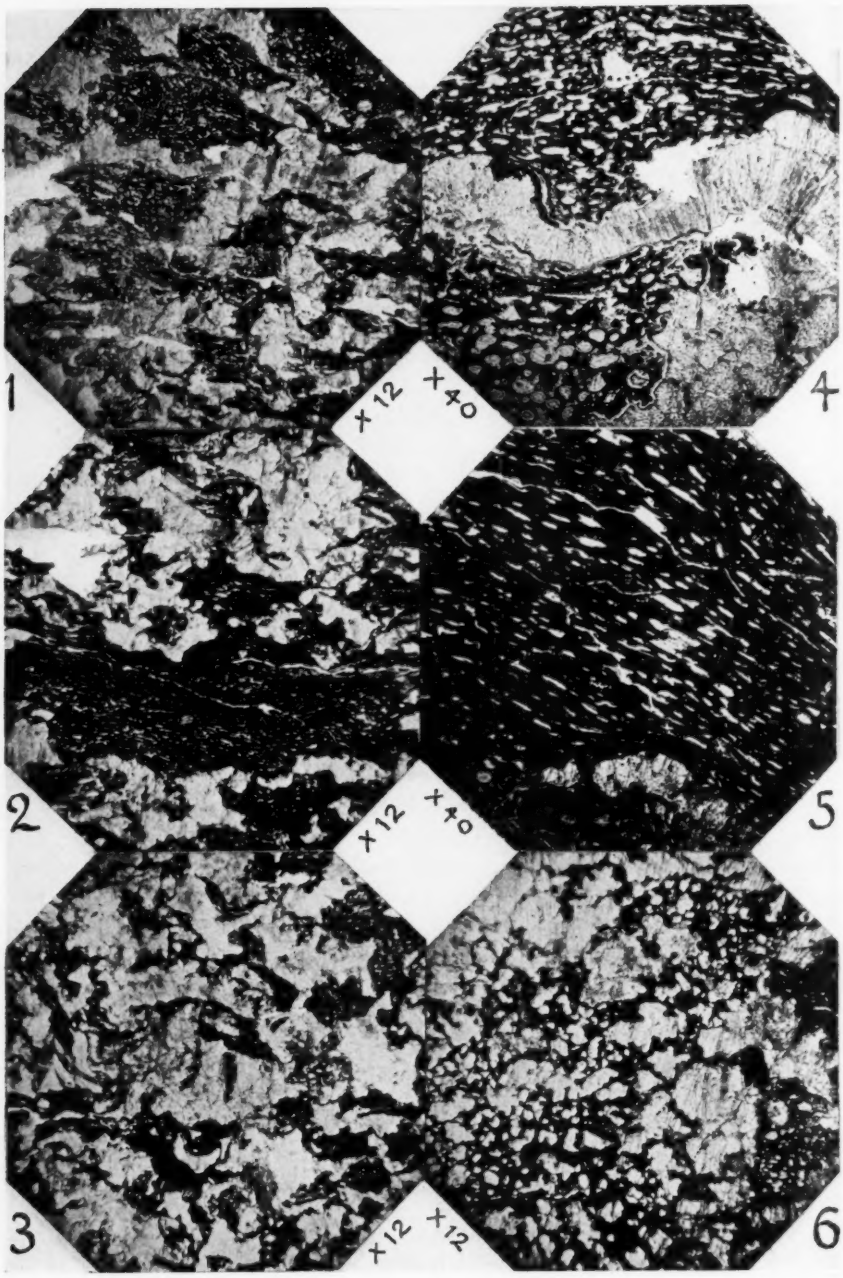
Microscope study soon showed that in his characterization based on the field occurrence Dr. Matley was correct: it was a tuff. Further study has shown, too, that it is albitic.

The rock is a coarse volcanic tuff, consisting of extremely irregular amygdaloidal lava fragments ranging, in the slices, from 12 millimeters to 1 millimeter and, in the rock specimen, from $2\frac{1}{2}$ centimeters down. It is strange, however, that with these fragments there is no trace of fine material of comparable character. The lava fragments accompanied by a few large mineral grains are, indeed, embedded in an abundant, colorless, fairly clear mineral matrix. The contrast between rock fragments and mineral matrix is strikingly complete.

Originally the fragments would practically all be highly vitreous and highly vesicular; but all vesicles are believed to have been completely closed by filling, though in many fragments much of this filling was subsequently lost when the vesicles were flattened out under deformation. Most fragments are partly translucent, the altered glass transmitting in thin section a khaki or grayish-olive color. All contain opaque, scattered hematite, many being very extensively replaced by it; and a few, which differ also in other ways, appear as if completely replaced. These differ markedly from the rest in having been more coarsely vesicular: the amygdales, moreover, in the single section of such a fragment, did not collapse and are filled with a different material. They would seem to represent a different part of the lava or a different lava, perhaps previously impregnated with iron (Figs. 6 and 7).

Representing the original volcanic glass of translucent fragments is a pale-green, doubly refracting substance, greatly obscured, especially near the surfaces of vesicles and therefore also of fragments, by dense crowds of rather highly refractive, minute, rodlike, practically colorless crystals (cf. leucoxene), thought to be anatase (Figs. 8 and 9).[2] Also at the bounding surfaces of the vesicles there is often a scattering of hematite, ranging from thin transparent

[2] Though at first thought to be sphene, the very small proportion of lime in the rock, 0.88 per cent, would seem to indicate anatase.


1
×12 ×40
4
2
×12 ×40
5
3
×12 ×12
6

films to opaque spherules, and sometimes a continuous hematite layer.

Apart from the disseminated "anatase," the altered glass appears fairly homogeneous—there is no trace of microlites, and it would appear to have been originally sideromelane.[3] Its birefringence is consistently oriented, and this orientation can confidently be attributed to deformation. The birefringence is strongest where consistent collapse of the amygdales and their parallel extension and dense distribution indicate strong, directed pressure. But even where the amygdales are practically spherical, giving between crossed nicols a good black cross, the double refraction in the surrounding altered glass is still strongly marked and is oriented like that in neighboring lava fragments. The direction of compression is that of the "fast" ray; that of extension—the "slow" ray. The refractive index of this substance is *higher* than that of balsam, being about 1.56, and its birefringence is sensibly the same as that of the first layer of chlorite filling the vesicles, where these are spherical. The orientation of its fast and slow rays, moreover, is the same as that of this chlorite in collapse; and the conclusion is reached that it also is crystalline chlorite.[4]

Phenocrysts are represented only by pseudomorphs after plagioclase and mafic minerals and are rare (see below).

All the lava fragments, except the few replaced by hematite, had their vesicles completely or largely filled with chlorite (Figs. 4, 8, 9, and 10). The first deposit of this is a substantial layer of sensibly colorless, relatively homogeneous, and structureless chlorite, which usually shows faint concentric lines of growth. Let us call it "Chlorite I." Its refractive index is least where the vesicles are round and rises with deformation to 1.57. Its birefringence again, which, in the spherical vesicles is sensibly the same as that of the

[3] M. A. Peacock, "The Basic Tuffs," Part I in Peacock and G. W. Tyrrell, "The Petrology of Iceland," *Trans. Roy. Soc. Edinburgh*, Vol. LV (1926), pp. 66 and 67.

[4] See pp. 226–27.

FIG. 1.—KP 312, slide *b* (cut across the shear surfaces and in direction of elongation). Ordinary light. ×12. Matrix of finely cracked analcite with some albite. Numerous shards, "opaque," except for amygdales and pseudomorphs after phenocrysts. Left of center a shard is little sheared: it is bordered by "Chlorites I and II"; and its eyelike amygdales are filled with the same. Above this is a shard with some opaque hematite outside the peripheral chlorite, with pseudomorphs after fragmented olivine to left and increasing deformation to right. These shards are seen in Figure 4.

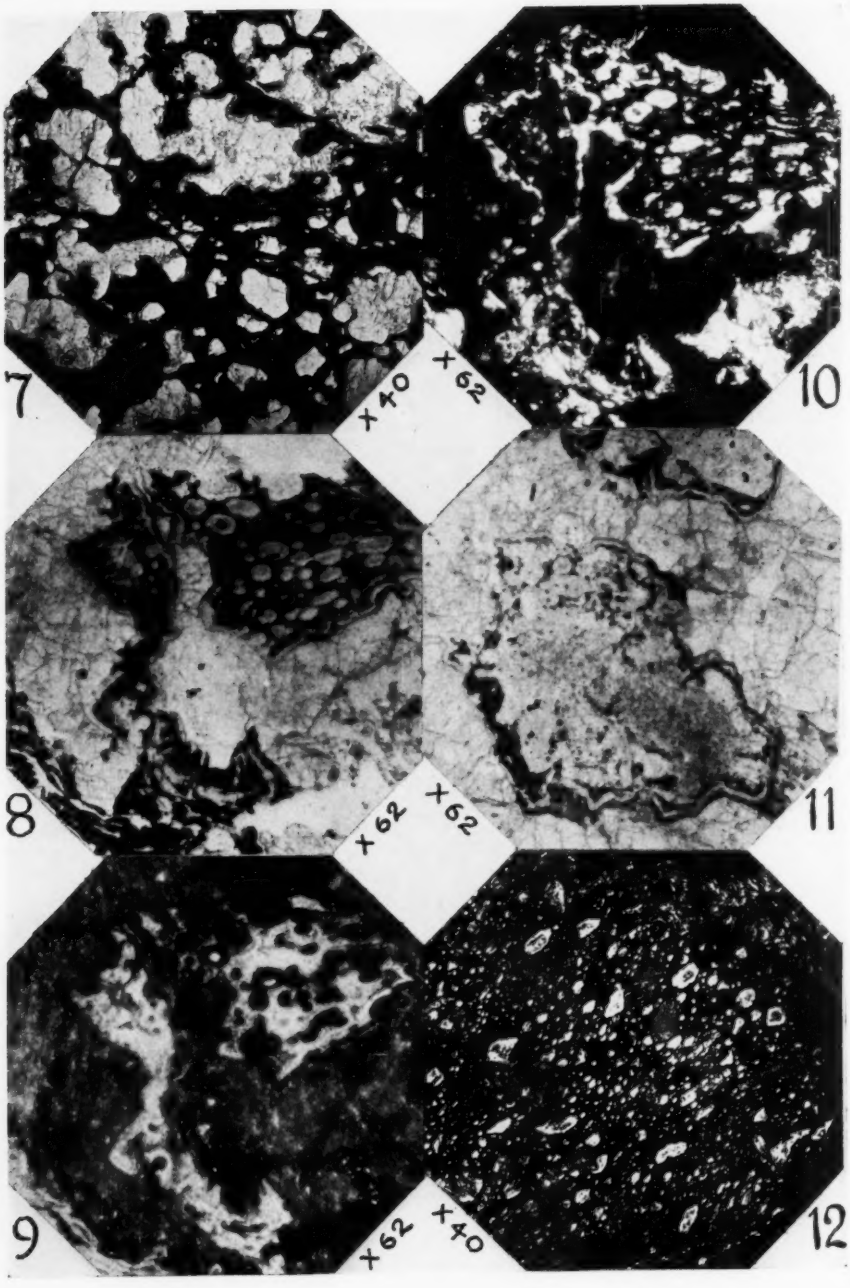
FIG. 2.—Same slide. Ordinary light. ×12. A large, well-sheared shard, with vesicles represented by lines of Chlorite I. Chlorite is absent from its extended surfaces. Matrix chiefly of analcite.

FIG. 3.—Same rock, slide *c* (cut across surfaces of shear and *across* direction of elongation). Ordinary light. ×12. The matrix here does not show the parallel cracking. The small sections of shards are mostly "opaque." In the center is a small upright shard, little sheared and with conspicuous peripheral chlorite. To the right is another with round vesicles filled with chlorites.

FIG. 4.—Same rock, slide *b*. Ordinary light. ×40. Part of same field as Figure 1. Systematically cracked analcite crosses the center and below, to the left, is a shard, little sheared, with subspherical vesicles filled with Chlorites I and II. Above, a moderately sheared shard contains a pseudomorph of chlorite after olivine, with octahedra of magnetite.

FIG. 5.—Same, slide *b*. Ordinary light. ×40. Part of a well-sheared shard with vesicles containing double bands of Chlorite I.

FIG. 6.—Same rock, slide *a*. Ordinary light. ×12. Part of a large, highly hematitic, coarsely vesicular shard. The vesicles are mostly filled with analcite. When entirely enclosed, this is little cracked. The peripheral vesicles mostly shown here are well cracked.


7
×40
×62
10
8
×62
×62
11
9
×62
×40
12

chlorite after the glass (half as high again as that of the analcite referred to below), rises considerably with deformation—indeed, up to three times the strength. Furthermore, both these properties usually increase in strength toward the inner (distal) limit of this chlorite, where the birefringence may be double its normal strength. Its optic orientation is definite: in subspherical amygdales the vibration direction of the fast ray is normal to the surface of the vesicle in all sections. In amygdales flattened by deformation the orientation is still the same, but now the whole is alike, with the vibration direction of the fast ray coinciding with the direction of compression (Fig. 5).

In most of the fragments the amygdales have been flattened out; in this case they may contain no other filling besides Chlorite I. In those fragments, however, where part or the whole of the sectioned amygdales are still subspherical, they are further filled with distinct chlorite "fibers" directed toward the center and having usually the same spatial optic orientation as Chlorite I, that is, the fibers have a −ve elongation, though not infrequently they may have a +ve elongation. Let this be Chlorite II.

Chlorite II is much coarser in texture than Chlorite I. Its optical properties may be about the same; but it has both higher refringence and higher birefringence, when the two chlorites can be seen together. Its texture suggests that it may possibly be an aggregate of two minerals. Both chlorites are almost colorless (very pale green) and have no appreciable pleochroism, but in one cavity is to be seen a hexagonal plate of Chlorite II with green color.

Several large vesicles, after having received Chlorite I and Chlorite II, were further filled with analcite, which sometimes shows rectangular cleavage. In this connection it may be noted that in sections of sideromelane and palagonite tuffs from Iceland, kindly lent by Dr.

FIG. 7.—KP 312, same slide, *a*. Ordinary light. ×40. Same hematitic, coarsely vesicular shard with amygdales containing analcite only or analcite with chorite border (external vesicles). Note the sparse cracks in the analcite.

FIG. 8.—Same rock, slide *c* (cut *across* the direction of elongation). Ordinary light. ×62. The analcite shows little systematic cracking. Two small, distorted shard sections shew peripheral chlorite with hematite. The "opaque" matrix of the upper right shard contains vesicles filled with translucent Chlorites I and II and in two vesicles opaque matter also.

FIG. 9.—The same field in reflected light. ×62. The "opaque" matrix of the shards is now white, especially in the well-sheared shard at the border (*left, below*), and the translucent chlorites are dark. The analcite and albite matrix of the rock is gray.

FIG. 10.—The same field in crossed nicols. ×62. The birefringent and radially arranged chlorites of the vesicles show a distorted bright cross on the black ground. To the right below, the matrix of the rock now divides itself into gray and black analcite and bright albite.

FIG. 11.—Same rock, slide *c*. Ordinary light. ×62. The two shards seen are chiefly chlorite after olivine; the upper includes octahedra of magnetite. Both show the peripheral chlorite layers associated with hematite.

FIG. 12.—Andesitic conglomerate, GH 23. Green filter and crossed nicols, with sensitive tint added. ×40. Except the top strip, part of a deformed pebble of amygdaloidal andesite with a few crystals of plagioclase. Practically all the bright areas are vesicles, the larger filled with "Chlorites I and II," the smaller with "Chlorite I" only. They are uniformly in position of brightest interference color for Chlorite I and are giving green and yellow of second order. Above to right is the interstice beyond the pebble filled with "Chlorite II."

Tyrrell for comparison with this Jamaica tuff, it is clear that the chlorite-depositing fluid did not diffuse through the glass but gained access to the vesicles along the abundant cracks. Small vesicles to which cracks gave access were completely filled with chlorite, while the corresponding deposit in large vesicles forms only a lining to their walls. The same is assumed to have been the case here. But in the vesicles of the lava fragment replaced by hematite the chlorite layers are usually quite lacking, the cavities being filled with analcite (Figs. 6 and 7). This absence of chlorite within the vesicles might be attributed to an absence of cracks through the hematite during the chlorite-depositing stage of alteration.

All the lava fragments, besides having their cavities filled with chlorite, are in general bordered all round by a continuous layer of the same, which fairly closely matches that lining the vesicles, even to its subdivision into two layers (Figs. 4, 8, and 11). Typically it consists of an apparently homogeneous layer similar to the Chlorite I, and like it in having the fast ray normal to the surface, usually bordered by a thin layer of chlorite crystals of higher refractive index but lower double refraction, doubtless representing Chlorite II. Usually both have the same orientation of birefringence, though this outer layer not uncommonly has +ve elongation. These chlorite borders are always present at the ends of fragments, but they may be absent locally from the faces of the fragments, a feature attributable to deformation.

The similarity of character of this external chlorite to the chlorite of the vesicles suggests that they are both parts of the same formation, which was subdivided into Chlorites I and II by some change in environment. In Icelandic tuffs several such changes in the chlorite are often visible.

These deposits of chlorite, however, both that outside the fragments and that within their vesicles correspond exactly with what Dr. Peacock regarded as palagonite, the *in situ* alteration product of basic glass, the former being, according to him, a marginal alteration, and the latter, spherulites developed within a palagonite or altered sideromelane.[5]

Interruptions of the vesicularity in the lava fragments mark original phenocrysts. These are of two types. One is constituted by irregular grains and a few well-bounded crystals of untwinned feldspar, usually as aggregates containing small grains of red hematite. Around these the lava is usually very opaque and in reflected light is white like leucoxene. This feldspar has a refractive index lower than that of balsam. Its association with hematite and leucoxene suggests that it is here secondary[6] and is thus a pseudomorph. It is referred to albite (or a plagioclase near albite).

The dominant type of phenocryst is represented by chloritic pseudomorphs, doubtless after a mafic mineral or minerals (Figs. 3 and 11). A pseudormorph of an isolated crystal has an outline and structure, which suggests an origin in olivine; it consists of coarse chlorite, both in sheets of transverse fibers bordering original cracks and in aggregates of sheaves. Where most markedly fibrous this chlorite has +ve elongation but exhibits both positive and negative. Its refringence and birefringence are both greater than neighboring Chlorite I. Within this pseudomorph are also opaque crystals of two kinds: one is possibly brookite (brown, rectangular, and

[5] See p. 233.

[6] See below under analcite, p. 223.

opaque), the other magnetite in brightly shining octahedra. Another very similar chlorite pseudomorph attached to a previously vitreous fragment has an external or first layer with −ve elongation like Chlorite I, while the rest has +ve elongation. Most of the chlorite in other pseudomorphs has also +ve elongation; many contain octahedra of magnetite.

In one slide only, out of three, occur a few crystals of greenish-gray epidote.

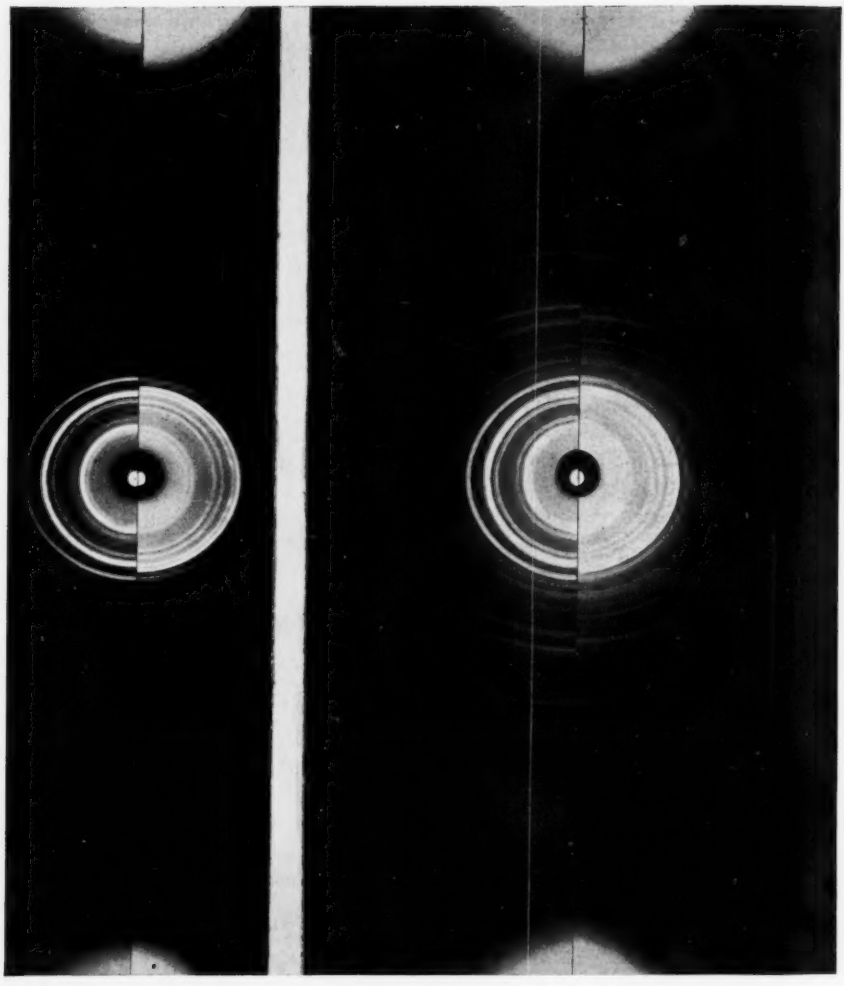
The mineral matrix of this tuff is extraordinary; it appears to constitute about half of the rock by volume (Figs. 1 and 3) and is of a type not perhaps described hitherto. White in the hand specimen, under the microscope it is seen to consist mainly of a single mineral identified as analcite. Irregularly scattered through it there is hematite in fine division, blood-red in reflected light.

In the discussion on this paper read at the Geological Society of London, Dr. L. Hawkes mentioned his experience of the impossibility of establishing the identity of the zeolites in tachylyte (sideromelane) sandstones of northern Iceland by optical properties alone. In a subsequent letter he suggested that it would be advisable to confirm the above identification of analcite by X-ray examination. Dr. Claringbull very kindly undertook the X-ray photography both of this analcite and of the albite which partly replaces it. These were isolated by the electromagnet, separated from one another by density, and submitted to Dr. Claringbull, who confirms the identifications as "analcite" and "a felspar close to albite," in states of comparative purity (Fig. 13, *A* and *B*).

This analcite exhibits a remarkable structure. Except in the hematized lava fragments, it is traversed by numerous subparallel cracks approximately normal to the extension of the fragments (Figs. 1, 2, and 4). Where the slide is thinnest and fewest cracks appear, there are still 30–50 cracks to 1 millimeter. The fissures range from fine lines to veins 0.05–0.18 millimeter across; but all are filled with chlorite and to a small extent with hematite, both of which are therefore here of later origin than the analcite. This system of fissures can be referred to deformation. In the larger veins it is quite obvious that the plates of chlorite lie parallel to one another across the fissures. This chlorite has mostly +ve, but often −ve elongation, the two appearing in neighboring parts of the same fissure. The birefringence is about 0.006.

Replacing parts of the analcite is a colorless mineral with a higher refringence, still, however, well below that of balsam (cf. Figs. 8 and 10). Frequently it is polysynthetically twinned, with discontinuous twin lamellas; it was identified as albite. It obviously postdates the fissuring of the analcite, for it is bounded frequently by the chlorite-filled fissures. These crystals are probably based on plagioclase nuclei in the lava fragments, contiguous to which they usually lie. It differs from the albite pseudomorphs of the lava in not containing hematite. In a few places also small areas of natrolite are present in the analcite. The albite would appear to be pure, for the natrolite and the albite have the same birefringence, measured in one case as 0.011.

In *reflected* light the appearance of the rock under a low magnification is very striking; and, owing to the obscuration due to secondary changes, this illumination is of great value as an aid to interpretation. The ground due to analcite is then dark- to light-gray, the latter where traversed by most abundant cracks: light-gray also are the areas in which analcite is replaced by albite.



ANALCITE × ALBITE
13A

ANALCITE × ALBITE
13B

FIG. 13.—Comparative powder-photographs (X-ray) of analcite and albite from matrix of KP 312, separated from other minerals by electromagnet and from one another by density. Photographed and identified by Dr. G. F. Claringbull. *A*, Strong prints for comparisons in center of field; *B*, light prints for comparisons in outer part.

The lava fragments present great variety according as they are hematized or not and according as they are traversed or not by the zones of intensive shear. Those not thus affected, and so having their vesicles subspherical, are pale sage-green in ground color, owing to a fine suspension of the colorless anatase in the green chlorite representing original glass; and they are spotted all over with the green amygdales—a dark-green ring of transparent Chlorite I enclosing the lighter-green Chlorite II. The amygdales may be outlined in brown hematite and are always surrounded by brighter borders due to surface concentrations of the anatase within the chlorite after sideromelane (Fig. 9). Comparatively rare are the phenocrysts—the dark feldspars with their specks of red hematite and the dark-green pseudomorphs in chlorite, some with flashing magnetite.

Where, on the other hand, the same lava fragments form a shear zone, they become white. This is probably due to concentration of the anatase, resulting from solution and removal of the enclosing chlorite under stress. Their amygdales, too, are reduced to subparallel dark-green lines. The courses of these shear zones are extremely wavy, as if torn by currents. Along them light-red to dark-brown hematite is much developed.

A most conspicuous contrast to these is a fragment replaced by hematite—dark brown, coarsely vesicular, and filled with dark-gray analcite.

MODE OF DEFORMATION

Owing to the heterogeneity of the rock, the different constituents, when subjected to deforming stress, exhibited marked differences of behavior.

The obvious evidences of deformation are as follows:

1. The flattening-out of the amygdales so that they are extended across the direction of compression
2. Frequent dislocation of the amygdales in the direction of their extension
3. The double refraction uniformly exhibited by the whole of the previously vitreous part of the lava fragments
4. The systematic variation in thickness of the external chlorite layer of the fragments
5. The system of fissures in the analcite, absent only in that within the vesicles of the hematized lava fragments
6. The relationship between the orientations of items 1–5
7. The filling of all the fissures in the analcite with chlorite, the origin of which can be traced to the development of items 1, 2, and 3

A few notes under items 1–7 will here be given.

1. The originally glassy lava fragments would seem to have yielded continuously, but in various degrees according to the different intensities of the stress, as explained below. On the other hand, the hematized lava fragments resisted (Figs. 6 and 7). They consist of little besides hematite replacing the lava and of analcite filling their undeformed vesicles, and both constituents contributed strength.

The flattening of the amygdales is part of a general deformation of the previously vitreous fragments, whereby the spherical amygdales were drawn out into elongated lenticles. Fortunately, all stages in the process are presented. Certain of them, relatively protected from shear by neighboring hematized fragments, are only slightly deformed, and these have their vesicles subspherical and completely filled with Chlorite I and Chlorite II, only the largest vesicles having in addition an analcite center.

In most of the fragments, however, the amygdales are thin, long, parallel-sided, and extended parallel to one an-

other; they are represented only by a double layer of Chlorite I with a distinct median parting. This condition is attributed to the collapse of the chlorite spheres under stress. Presumably their content of Chlorite II was gradually eliminated, owing to a weaker resistance. That this layer was previously present in all but the smallest vesicles is suggested by the fact that all degrees in its representation down to its total absence can be seen and by the character of the external chlorite layer of the lava fragments, which also clearly consists of Chlorite I and Chlorite II.

2. Certain lava fragments, where subjected to especial shear, have slip planes running through them, which are traced by their dislocation of the amygdales. In some fragments, again, where the amygdales are subspherical and their walls strengthened with hematite, these are often dislocated in accord with the local deformation.

3. By their closely spaced lines of elongated vesicles most of the lava fragments at first give a wrong impression of great flow when viscous. Such flow, by itself, would leave the fragments perfectly vitreous and inert between crossed nicols; also it would not explain the uniform presence of the sharp division between the two halves of the layer of Chlorite I within their vesicles. On the other hand, besides the above-mentioned evidences of deformation, in every fragment, whether the amygdales are flattened out or subspherical, what had been glass is doubly refractive. This birefringence, moreover, is definitely oriented in such a way that the direction of compression in the fragment is the direction of the fast ray and that of elongation the slow ray (strikingly seen when the slice is examined between crossed nicols and the sensitive, violet-tint plate inserted). Even in those fragments where the vesicles are spherical and no other evidence of deformation is pronounced, the altered glass is seen to have nearly the same double refraction as the Chlorite I of the amygdales and to agree with neighboring collapsed amygdales in optic orientation. With increase in the degree of deformation, as indicated by the progressive flattening of the vesicles, the birefringence rises. It is a most striking phenomenon. Every originally vitreous lava fragment in three sections, each 2 inches long, exhibits this property. As before stated, the material seems to have become chlorite. For this material, previously vitreous, now agrees closely with neighboring chlorite in color, refractive index, and in the amount and orientation of its double refraction.[7] This last-named feature would appear to have been induced by stress, since it bears such a definite relation to the direction of compression indicated in several other ways. Though the orientation agrees with that exhibited by artificially stressed glass,[8] the effect differs from this in being permanent and strong.

This transformation of basic volcanic glass into chlorite is not difficult to conceive after comparison has been made with sideromelane and palagonite tuffs. The lava fragments were in each case chilled basic glass (sideromelane), which water action changes into palagonite.[9] Dr. M. A. Peacock has given an account of the process in a number of pa-

[7] In other rocks in which it is more transparent it exhibits pleochroism also and is similarly oriented (see pp. 237, 240–41).

[8] E.g., Hardy and Perrins, *Principles of Optics* (New York: McGraw-Hill Book Co., 1932), p. 613.

[9] It seems unnecessary to discuss the nature of palagonite or its relation to chlorophaeite. The author's standpoint is expressed in the discussion on this paper after its reading (see Raw, *op. cit.*, pp. 68–69).

pers; and his slides are in the Glasgow University geological collection. Hence, for comparison with this Jamaica tuff, close study has been made of a collection of 40 slices of sideromelane and palagonite tuffs from Iceland, kindly lent by Dr. Tyrrell and Professor Trueman. In these, all stages in the transformation of sideromelane into palagonite are exhibited. Peacock has claimed that the change is accompanied by hydration, by oxidation of the iron, and by loss of lime and soda. This would bring the glass toward the composition of a chlorite. Often the palagonite is isotropic; but sometimes it is a birefringent substance, oriented in accordance with the surface from which it grew, perhaps controlled in its crystallization by previously deposited chlorite. In all cases probably, when the palagonite has attained stability, it will have the composition mainly of a chlorite. Presumably the effect of stress has been to purify by crystallization and to control the orientation.

4. Around fragments protected from deformation by the hematized fragment, which is at the same time the largest, the external chlorite layer does not vary much. But around a normal deformed fragment this layer varies in thickness greatly and systematically. On the shear surfaces it is attenuated or, where a fragment is greatly drawn out, absent altogether, owing to removal by solution from a surface of compression. This was accompanied by recrystallization across a direction of tension (see below).

5. The systematic fissuring of the analcite is a most striking feature, giving a definite pattern to the analcite areas. Except in the amygdales of the hematized lava fragment, the whole of the analcite is affected: the close-set cracks extend across the direction of elongation, which is indicated both by the flattened amygdales and by the direction of the slow ray in the adjoining lava fragments.

The variation in the direction of the cracks, from subparallel to radiating, is explicable by the constant variations in the directions of the shear zones running through the irregular and irregularly spaced "vitreous" fragments, which involved bending, as well as tensile stress in the neighboring analcite. Apart from this cracking and opening of fissures, the analcite has suffered no visible deformation. The cracking has relieved the strain natural in the mineral, for these cracked areas exhibit lower birefringence than is shown by the same mineral within the undeformed vesicles. This fissuring of the analcite suggests that the uniform pressure accompanying the stress was relatively low.

6. All the fissures, in which the width can be appreciated, are found to be filled with chlorite closely similar to the Chlorite II of the subspherical vesicles and of the "external chlorite layer." Like these, the sign of its elongation varies. Wherever the structure of a chlorite vein can be seen, the chlorite flakes or fibers extend across the fissure, and they are thus fibrous veins. Their aggregate thickness in proportion to the analcite furnishes a minimum value for the stretching of the latter.

In sections across these veins there is no center line; hence they do not seem to have originated by the filling of open fissures; indeed, had this been the case, we might expect fans and sheaves of chlorite in them. On the contrary, chlorite growth would seem to have kept pace with the stretching and to have maintained continuity. In support of this is the fact that the chlorite fibers maintain their parallelism, though the fissures change direction. The veins suggest a very gradual process of elongation.

Small parts of fine veins may be occupied by hematite. The fact that chlorite is the only mineral extensively taking part marks it as a low-temperature effect.

The deformation evidently constitutes a low-grade metamorphism. This is indeed fortunate, for it is this feature which enables one to analyze the deformation, to picture its progress in detail, and also to visualize the predeformation stages of alteration.

The determining factors readily divide themselves into (1) the mineralogy and lithology of the affected rock and (2) the physical conditions inducing and accompanying deformation.

Originally the rock was, one judges, a particularly pure sideromelane tuff. But sideromelane, being vitreous and basic, is highly unstable; it would all have been altered, given suitable conditions; and reasons have been given for assuming a change into palagonite. This substance is highly hydrous and soft and would readily give way under stress. In sections of Icelandic palagonite tuffs, in which zeolites are scarce or absent, one can note how the palagonite has collapsed like a watery sponge, presumably under gravitation, proving less resistant than the crystallized chlorite, which occurs as spherules filling vesicles and as borders to the fragments, and very much less resistant than the zeolites.

In our rock the beautiful preservation of the textures in the shards shows that such collapse was inhibited, which indicates that, as is the case in Icelandic rocks, palagonitization was largely deferred until the spaces of the rock had been filled with chlorite and analcite. The great abundance of analcite, which constituted a continuum, gave rigidity to the rock as a whole. To this strength the iron ore also would contribute. Originally deposited, probably, largely as limonite, this would appear to have changed into hematite before or during the deformation.

Ignoring the content of iron ore as being subsidiary, the successive conditions of the rock up to the onset of stress appear to have been: (1) a sideromelane tuff; (2) a sideromelane tuff impregnated with chlorite; (3) a sideromelane (and palagonite) tuff impregnated with chlorite and further completely filled and cemented by analcite; (4) the same, but completely palagonitized.

Remove the effects of stress, and one sees the tuff as a coarse aggregate of discrete fragments of lava of two very different resistances, a few being changed to resistant hematite, the rest converted to weak palagonite, and all within a voluminous continuum of crystalline analcite.

Under the stress the coarse texture combined with the very different behaviors of these three main constituents entirely prevented any uniformity of deformation within the rock. There are no shear "planes" but only extremely irregular shear surfaces. By the distribution of mineral composition the flow is largely limited to a three-dimensional network, the strands of which have very wavy courses of extremely varied thickness; for the flow traversed especially the pieces of palagonitized lava, avoiding the hematized fragments and the analcite, though cracking the latter and dragging it asunder. The courses of the cracks in the analcite can be directly connected with this irregularity of the flow.

All the processes of deformation were in operation at the same time. We can directly connect the deformation of the palagonite with that of its amygdales, though the palagonite responded more readily to the stress, all of it becoming

birefringent, even where the vesicles remain spherical. This weakness and extension of the palagonite allowed the stress to crack and extend the analcite. And, concurrently with all these, the interstitial water was, under stress, dissolving chlorite from the amygdales, from the external sheared surfaces of the palagonitized shards, and also out of the palagonite itself. This chlorite, moreover, the water was carrying to the cracks in the brittle analcite, keeping them filled all the time as they widened.

F. W. Clarke recounts the artificial formation of analcite in four different ways at temperatures of about 180° C.[10] In cooling it suffers inversion to some other crystalline state, as does leucite at a higher temperature. Hence these minerals may be under intense strain. Both analcite and leucite are notably brittle. Can the strain be in large part the cause of the brittleness?

Still other mineral changes which have affected the rock can best be attributed to this period of deformation. The irregular feldspars of the shards are albite carrying disseminated hematite and are doubtless secondary after basic plagioclase. Comparisons with Icelandic palagonite tuffs suggest that the basic feldspar would survive the palagonitization unaltered. Also it may be noted that one of the three slices of this rock contains a small amount of epidote, which could originate from lime feldspar. Both these minerals—albite and epidote—are common effects of stress metamorphism; and this is probably their mode of origin here.

Perhaps it is exceptional for the contrasted behaviors of the several constituents under stress to be so clearly marked and so clearly separable from one another. Had the deformation been greatly extended, these different behaviors might have been overlooked, owing to a spreading and intermixture of the constituents and a consequent confusion of their effects.

[10] "The Data of Geochemistry," *U.S. Geol. Surv. Bull. 770* (1924), p. 373.

SYSTEMATIC POSITION AND DEVELOPMENT OF THE ROCK

Ignoring minor changes, at least five different stages comprised the development of this rock. They are given in the summary on page 242 and are discussed below. Closely comparable stages can be seen in the microsections of Icelandic sideromelane and palagonite tuffs from Glasgow University, already mentioned.

STAGE I. INCOHERENT, VESICULAR SIDEROMELANE TUFF

Only this first stage was purely igneous. It was pyroclastic, peculiar in consisting almost entirely of vitreous lapilli without volcanic sand or dust, and was therefore extremely porous. Measured with the Dollar integrating micrometer, the spaces between the lapilli prove to have been equal in volume to what now represents the lapilli themselves. If to this be added the volume of the vesicles within the lapilli, which in many fragments was much more than half their volume, the aggregate porosity must have reached about three-fourths of the volume. Such an extremely porous deposit could not have sustained itself in air except to a relatively slight depth. Water, however, would give support, indicating that the rock must indeed be an aqueous deposit owing its character to the conditions of deposition.

A few fragments had already suffered extensive impregnation with iron before accumulation. They had evidently had a different history from the rest.

The typical lapilli (except for sparse

phenocrysts) appear to have been almost entirely vitreous without even microlites. What remains of them now is practically all chlorite, the dominant phenocrysts, as well as what represents the glass, consisting of that mineral. Further, the lapilli are coated and filled with chlorite. These features indicate a basic rock; indeed, the proportions of pseudomorphs apparently after olivine suggest the vitreous equivalent of an olivine basalt.

The vitreous nature of lapilli of a composition so basic implies the sudden chilling of a magma thoroughly fluid except for its phenocrysts, whose scantiness can be referred to the high temperature from which the chilling was effected. For such clear vitreous basalts Peacock has suggested the revival of von Walterhausen's name, *sideromelan*,[11] anglicized into "sideromelane."[12] Such glass is black, but in thin section it is transparent, clear, and yellowish in color, and its only minerals are the early-formed constituents—olivine or feldspar or both. Peacock (1924–25) has accounted for the high proportion of olivine by the fact that the early chilling inhibited reaction. Sideromelane contrasts with tachylite by its transparency and freedom from crystalline matter.[13] It is characteristically developed as a skin on submarine lavas and as the lapilli of submarine tuffs.[14]

Peacock and Fuller recognized it also where a Columbia River plateau basalt entered a fresh-water lake;[15] and other occurrences are recorded by W. M. Chappell.[16] G. V. Wilson also records an Eocene instance in the Island of Skye.[17] It is especially characteristic of Icelandic tuffs, which Peacock referred to subglacial extrusions.[18] This last mode of origin for sideromelane has been supported by N. Nielsen and A. Noe-Nygaard[19] in 1936; likewise by T. F. W. Barth in 1937,[20] who found that subglacial extrusions of volcanic ash from Vatnajökull both of 1922 and of 1934 gave rise to practically identical sideromelane tuffs. From sideromelane, and from this alone, Peacock derived palagonite, fibro-palagonite by the action of hot water, gel-palagonite by the action of cold water under pressure.[21]

Extrusion into cold sea water would fit what is known of this Jamaica tuff, and sudden chilling of an olivine basalt magma would give rise to a glass with a preponderance of olivine phenocrysts.

Such unchanged vesicular sideromelane without filling by chlorite or zeolites is seen in the slide entitled "T119. Tuff of Sideromelan and Hyalo-basalt. ? Till. Mouth of Stora Valagil, Tindfjallajökull, Iceland, Geol. Dept. Glasgow University Coll"; and it contains a small proportion of opaque, black, vesicular lava fragments.

[11] Tyrrell and Peacock, *op. cit.*, p. 56.

[12] M. A. Peacock and R. E. Fuller, "Chlorophaeite Sideromelane and Palagonite from the Columbia River Plateau," *Amer. Min.*, Vol. XIII (1928), p. 360.

[13] Peacock, "The Basic Tuffs," *op. cit.*, p. 66.

[14] *Ibid.*; "The Volcano-Glacial Palagonite Formation of Iceland," *Geol. Mag.*, Vol. LXIII (1926), p. 461.

[15] *Loc. cit.*

[16] "The Effect of Miocene Lavas on the Course of the Columbia River in the Center of Washington," *Jour. Geol.*, Vol. XLIV (1936), pp. 379, 382–84.

[17] *In Summary of Progress of the Geological Survey of Great Britain for 1935*, Part I, pp. 81–84.

[18] "The Vulcano-Glacial . . . . ," *op. cit.*, pp. 460–63.

[19] "Om den islandske 'Palagonitformation' Oprindelse (Entstehung)," *Geog. Tids. (k. dansk geog. Selsk.)* Vol. XXXIX, Part II (1936), pp. 89–122.

[20] "Volcanic Ash from Vatnajökull: A Modern Formation of Sideromelan," *Norsk. Geol. Tids.*, Vol. XVII, Part I (1937), pp. 31–38.

[21] Peacock, "The Vulcano-Glacial . . . . ," *op. cit.*, pp. 70–71, 74. His fibro-palagonite is, however, referred below (pp. 233–35) to deposited chlorite.

Very vesicular sideromelane, again, but with extremely thin deposits of chlorite with "+ve elongation" and with incipient formation of palagonite (as hemispherules), is seen in "X8. Sideromelane tuff. Kverkfjöll, N. Margin of Vatnajökull, Iceland," which is awaiting description by F. W. Anderson and G. W. Tyrrell. This is the closest match to this hypothetical Stage I.

STAGE II. EXTREMELY POROUS, AMYGDALOIDAL SIDEROMELANE TUFF

Following a slight development of ?limonite, now hematite, the first important change was the deposition of Chlorite I and Chlorite II, each in succession coating the shards and also filling their vesicles. The relations and the differences between Chlorite I and Chlorite II suggest that I was formed at higher temperature and more rapidly than II. That these deposits preceded any extensive palagonitization of the sideromelane has already been claimed above.

The nature of the lapilli during and after the impregnation by chlorite can be judged by comparisons with sideromelane tuffs from Iceland and a recent sideromelane and palagonite tuff from Samoa in the Waller Collection of the Geological Department, Birmingham University—"374 Palagonite, Samoa, probably Upolu."

The bulk of the Samoan rock consists of highly vesicular fresh sideromelane fragments, which are separated by palagonite. The glass of the larger lapilli is of a dull, greenish-yellow color and devoid of microlites or trichites. Fresh olivines in well-shaped crystals are the only phenocrysts. All the larger vesicles are lined with a substantial layer of doubly refracting material, apparently representing our Chlorite I. It is paler and less refractive than the glass, a purer yellow in color, apparently homogeneous, and with a refractive index of about 1.55. The birefringence is weaker than that of Chlorite I, but it agrees with this both in optic orientation and in the fact that the deposit begins and ends with material of higher birefringence. It seems probable that in this Samoan sideromelane we have exhibited an early stage in the formation of the mineral of our Chlorite I. In both cases we seem to have the equivalent of the celadonite priming of agate amygdales. This, however, has a "+ve elongation"—a feature perhaps of little significance. There are some minute vesicles without this deposit and still filled with gas; for only those vesicles to which cracks lead receive the deposit. The smaller of these are filled completely, the larger contain a central space. The fresh sideromelane in the section is quite distinct, both from this birefringent lining of its vesicles and from the deeper and brighter yellow cryptocrystalline "palagonite." This palagonite results here in part from the hydration of massive sideromelane containing vesicle linings similar to those just described, but especially from hydration of the finely divided material between the larger lapilli. The angular spaces filled with this material are lined throughout with a layer of the same mineral that lines the vesicles, corresponding, therefore, with the layer of Chlorite I round the lapilli of our tuff. Both within the vesicles and in these irregular spaces it is clear that the birefringent layer is a *separate deposit* and not merely a modification of glass or of palagonite. For in four cases olivine bounds a vesicle and in one case projects into it, but in each case the layer is of just the same width past the olivine, which would not be the case were it replacing sideromelane, as is claimed by Peacock. Again, in the linings of the angular rock

spaces there is no difference in its character when bordering glass and when bordering "palagonite."

An example from Iceland with comparable amygdaloidal lapilli is "X93. Sideromelane tuff from Kverkfjöll, north margin of Vatnajökull, Iceland," awaiting description by Anderson and Tyrrell. The very vesicular sideromelane fragments have their vesicles, where cracks reach them, filled wholly or partly, according to their size, with chlorites. Bordering the deposited chlorites, the glass to a small extent is altered to palagonite, which, indeed, here is a *chlorite* with the same orientation of birefringence as the deposited chlorite!

The material for the deposit of Chlorite I and Chlorite II in our tuff can most reasonably be derived by decomposition (palagonitization) of comminuted sideromelane elsewhere in the deposit or of a pre-existing sideromelane tuff at a lower level.

At the close of this stage, judging from Icelandic examples, the palagonitization of the glass would have only just begun.

STAGE III. COMPACT, ANALCITE-CEMENTED AMYGDALOIDAL, SIDEROMELANE (AND PALAGONITE) TUFF

The next changes involved a relatively enormous accession of mineral matter. After some deposition of iron ore, now represented by hematite, the remaining spaces in the rock—those between the lapilli, which still constituted about 45 per cent, and those of the largest vesicles, which the deposits of chlorite had not completely filled—were now filled up with analcite.

The large volume of the analcite and the preservation to so large an extent of the original structures of the lapilli suggest that its deposition was very rapid—much more so than palagonitization. The material for so copious a deposit cannot, so easily as in the case of the chlorite, be derived by decomposition of igneous rock elsewhere. Its great preponderance suggests the need of a further source of soda, most probably the salt of the sea.[22] This, reacting with fine volcanic ash with or without the aid of volcanic heat, would be a sufficient source. No great elevation of temperature would seem to be needed.

Analcite occurs very abundantly in the deposits of some salt lakes which have received volcanic ash, as described by W. H. Bradley[23] and C. S. Ross[24] in the United States. In these cases sun heat may have been a factor.

No rock closely approaching this stage in the *proportion* of its constituents can be cited. But among the collection of slides from Iceland are some which appear to be completely filled with chlorite and zeolites, without much decomposition of the sideromelane having taken place. For example, "X7. Palagonite tuff, 'Yellow Tuff,' from Kverkfjöll, N. margin of Vatnajökull," to be dealt with in an unpublished work by Tyrrell and Anderson, is a tuff of sideromelane mixed with relatively opaque, vitreous lava fragments, all of them highly vesicular. The fragments were partly filled with pale olive-green chlorite with "+ve elongation"; then further filled with analcite and with calcite in scattered crystal grains. The sideromelane of some fragments has subsequently become extensively palagonitized. The proportions,

[22] The writer from his first acquaintance with spilites has always attributed their soda to this source.

[23] "The Occurrence and Origin of Analcite and Meerschaum Beds in the Green River Formation of Utah, Colorado, and Wyoming," *U.S. Geol. Surv. Prof. Paper 158-A* (1929).

[24] "Sedimentary Analcite," *Amer. Min.*, Vol. XIII (1928), pp. 195–97.

however, both of chlorite and of zeolite, are much less than in our rock, a difference in harmony with the contrast between terrestrial and marine conditions.

STAGE IV. ANALCITE-CEMENTED, AMYGDALOIDAL, PALAGONITE TUFF

The next change—the completion of palagonitization of the sideromelane, in the now compact rock—would probably occupy a much longer time than the preceding stages combined. Reasons have already been given for the conclusion that this change could not have preceded the deposition of analcite.[25]

It must have been effected by slow diffusion and was controlled by constancy of volume. That such a control was exercised here is indicated by the perfection of the vesicular texture in those shards which have been little deformed. It is well demonstrated by the Videy tuffs described by Peacock. These are only partly palagonitized and are thus sideromelane and palagonite tuffs. The sideromelane has very marked flow texture, which is equally evident in the palagonite. At the junction of these there is no change in the directions of the flow bands, showing that the change to palagonite was accompanied by no change of volume, notwithstanding the great accession of water. Peacock figured a microsection of one.[26]

The resulting rock is approached in qualitative composition, though not in quantitative, by specimens from Iceland in the Glasgow University collection. Two slides described and figured by Peacock will serve for comparison.

Slide S 30 is labeled "Palagonite rock with gelpalagonite and zeolites: South shore of the Hvalfjördur, Iceland. A massive bed underlying the Glacial lavas of the Mulafjall." According to Peacock, it consists of sideromelane, 3 per cent; palagonite, 76 per cent; chlorite, 14 per cent; and zeolites, 7 per cent. "The palagonite," he stated, "is isotropic, and its minimum refractive index is close to 1.500."[27] In color it is "yellow-brown" or "yellow-green."

> The palagonite has partly crystallised with the formation of chlorite and zeolites. . . . . This alteration [into chlorite] has resulted in vermicular and spherulitic aggregates. The former is displayed in the palagonite films which fuse together adjacent palagonitised sideromelans; the latter is assumed where crystallisation has commenced spontaneously within larger palagonite areas. . . . . The zeolites occupy the circular centres of the chloritic spherulites and the central sinuous areas of the vermicular patches.[28]

He identifies the chlorite as clinoclore and finds in the zeolite analcite, faujasite, and stilbite.

Inspection of the photographs[29] suggested a quite different interpretation, which the study of this and other slides has confirmed.

The paper described nine rock slices of sideromelane and palagonite tuffs and discussed their origin. In no less than seven of these slides, all of which are in the Glasgow collection, the vesicular lapilli are found to be coated, and their vesicles filled with chlorite; this, however, he claimed to be a secondary alteration product of sideromelane, formed by crystallization of palagonite. On the contrary, the writer finds that the deposition of chlorite mostly preceded the alteration of the sideromelane into palagonite,

[25] See above, p. 228.

[26] See Peacock, "The Vulcano-Glacial . . . . ," *op. cit.*, Fig. 4, p. 395.

[27] It is, however, in the slice studied higher than that of the balsam mountant and must be at least 1.54, depending probably, in such hydrous material, on the treatment accorded to the rock section.

[28] *Ibid.*

[29] *Ibid.*, Figs. 4 and 5.

for in several rocks chlorite coats unaltered sideromelane. The initial boundary of the chlorite is sharp and even, being based on the smooth surface of bubbles in—or of fractures through—the glass. These same surfaces are the initial surfaces of "palagonite," if we mean by this term the *in situ* alteration product of sideromelane: the other boundary, existent when palagonitization is incomplete, is, on the other hand, extremely irregular. The zeolites, again, which also he claimed as products of the alteration of palagonite, were likewise deposited for the most part before extensive palagonitization of sideromelane had taken place; hence these zeolites have no filial relationship to the palagonite in which they occur.

Peacock's "vermicular aggregates" of chlorite are usually the external coats of lapilli; but sometimes the linings of large internal vesicles, when greatly distorted by collapse of palagonite, present similar vermicular forms. His "spherulitic aggregates" are *in every case* the fillings of vesicles. Their growth has been from the circumference inward, not from the center outward. That this is the case is supported by four facts:

1. The "spherulitic aggregate," as he stated, is often an annulus enclosing a zeolite, that is, a vesicle filled with the successive deposits of chlorite and zeolite.
2. The exterior of the supposed "spherulites" is the smoothest curve among the lines of growth both of chlorite and of palagonite, being, indeed, the boundary of a bubble.
3. The minerals, both chlorites and zeolites, occupying such spheres often form hemispherical aggregates radiating from points on the initial bounding surfaces (the lines of growth thus indicating the directions of growth).
4. The supposed spherulites, where adjacent, do not coalesce, being still separated by what was originally the glass between the bubbles. (For these points see also Slide T83. "Palagonite tuff with fibro-palagonite, N. Bank of the Markarfljot . . . . Torfajökull, Iceland.")

Besides "S. 30" with which this Stage 4 has been compared, a similar comparison can also be made with slide T12. "Palagonite rock with gel-palagonite, zeolites and chlorite, Austurlith, 4 miles S.W. of Geysir, Iceland," which was interpreted by Peacock in the same way; for example, he stated: "The isotropic palagonite has been partly altered with the production of a pair of complementary minerals, chlorite and analcite." These, on the contrary, can be confidently claimed to have been in existence previous to palagonitization of the sideromelane.

To a long extension of the period of palagonitization can also be referred the decomposition and hydration of the olivine phenocrysts. In the Icelandic tuffs palagonitization appears always to precede attack on these phenocrysts. Palagonitization surrounds the phenocrysts with an aqueous medium, which favors their alteration and is necessary for serpentinization. But, whereas the olivine was doubtless altered here, albitization of the basic plagioclase is more probably referred to deformation. That the alteration of the olivine is not later than the deformation is suggested by the fact that the chlorite of which they now consist, largely agrees in the orientation of its double refraction with that of the other chlorites of the lapilli.

STAGE V. SHEARED AND ALBITIZED, ANALCITE-CEMENTED, AMYGDALOIDAL, CHLORITIC TUFF

The deformation and the accompanying mineral changes (of palagonite into oriented chlorite, of basic feldspar into albite, and a small formation of epidote) that led to this stage have already been discussed.[30] Probably they are part of

[30] See pp. 225–30.

the low-grade, dynamometamorphism accompanying the development of the Antillean chains, the climax of which has recently been referred to Pliocene time.[31] Had the grade of metamorphism been higher, the rock might have become a richly albitic chlorite schist, and its early stages of development would not have been decipherable.

For much chlorite schist and albitic chlorite schist palagonitization followed by dynamometamorphism may well have been the essential stages, as suggested by this rock: by the first change a composition, essentially of chlorite, was effected; by the second, purification, orientation, and the development of a new structure.

STAGE VI. THE SAME, MODIFIED BY ALBITIZATION OF ANALCITE

Still later than the Antillean orogeny and possibly at some elevation of temperature, albite grew at the expense of analcite, probably on albite nuclei in the lapilli. That this postdated the deformation is indicated by the fact that the growth of albite is frequently bounded by the chlorite veins.

DESCRIPTION OF THREE TUFFS AND A VOLCANIC CONGLOMERATE FROM THE GUY'S HILL ROAD SECTION, NORTH OF SPANISH TOWN, JAMAICA

Except for the presence or quantity of zeolite, phenomena similar to those described above (KP 312) would seem to characterize numerous Jamaican volcanics, and especially tuffs, as is indicated by the discovery of other tuffs and a volcanic conglomerate exhibiting much the same phenomena in a rock collection from a neighboring locality.[32]

This series of palagonitic rocks is of Upper Cretaceous age and comes from cuttings along the Guy's Hill Road between 22.2 and 22.4 miles north from Spanish Town. The section traverses an inlier of Cretaceous surrounded by Eocene rocks. The oldest rocks exposed (above the twentieth mile post) are andesite lavas, with tuffs interbedded in the upper part. These are overlain by ashy limestone and tuffs, and immediately beneath the first massive Cretaceous limestone and at about 22.2 miles is the peculiar deposit (GH 22).

GH 22

Labeled "red clay" or "marl," it is purple-chocolate in color and closely resembles a fine-textured sample of Etruria Marl from South Staffordshire. On the other hand, when broken down with ammonia water it yields very little clay; instead, angular fragments of all grades up to 5 millimeters form the bulk of the deposit. All are deep red in color and are impregnated with ferric oxide (hematite or near it).

When chemically cleared of iron, all the fragments are alike fine textured, soft, and whitish, and appear to belong to the *same* rock type; no limestone fragments or quartz occur. A section was obtained of about two dozen of these fragments *after* removal of the iron (with $SnCl_2$ in HCl). All are found to have the same structure and texture—that of vesicular vitreous lava with more or less collapsed vesicles filled wholly or partly with a *colorless transparent* chlorite. Some are further filled with opal-like chalcedony (brown in transmitted, blue

[31] Charles Schuchert, *Historical Geology of the Antillean-Caribbean Region* (New York: John Wiley & Sons, 1935), p. 37; A. C. Waters and H. D. Hedberg, "The North American Cordillera and the Caribbean Region," *Regionale Geol. der Erde*, Vol. III, Part IV A (1939), p. 40.

[32] Matley and Raw, "A Road Section near Guy's Hill, Jamaica," *Geol. Mag.*, Vol. LXXIX (1942), pp. 241–52.

in reflected, light). What represents the glass is partly obscured by very minute, highly refractive crystals, dark in transmitted, white in reflected, light. These are especially concentrated in the *walls of the vesicles*.[33] They are possibly referable to anatase but are too small for identification. All the material representing the original glass is otherwise colorless and transparent and is remarkable for exhibiting about the same birefringence as the chlorite which fills the vesicles. Further, in each fragment the orientation of the double refraction is constant, the direction of compression suggested by the rock texture being that of the fast ray. Crystals and microlites are few, though their outlines can be recognized; and they, too, are replaced by a substance with low birefringence oriented like that representing the glass! Thus *all the transparent material of a section is birefringent with the same orientation.*

These results were confirmed by the study of sections of the untreated rock, for, though because of the disintegrating action of water upon it the ordinary method of sectioning was impracticable, sections were obtained by dry grinding. Though much obscured by iron, these show that the chlorite in this is colorless and transparent, suggesting that there has been segregation of the iron into the matrix. They also display a uniformity of orientation of the chlorite throughout the whole section.

The rock is therefore comparable with KP 312, though there are important differences between them. The only phenocrysts here appear to have been olivine, so chilling may have occurred from a higher temperature. The product after glass is transparent, which fact suggests a smaller content of titania. The impregnation—with iron oxide instead of analcite—does not hold within it the same suggestion of marine conditions. There is here no evidence of oriented shear: the effects, so far as they have been seen, might be due to shrinkage by solution under the stress of mere loading.

The rock is best designated a "ferruginous palagonite tuff." Like KP 312, it probably indicates a subaquatic volcanic eruption.

[33] Cf. above, p. 223.

GH 23

Later than the volcanic tuffs, of which the last is a palagonitic example, and coming between the second and third Cretaceous limestone at about 22.3 miles, there is a volcanic conglomerate, GH 23.

The hand specimen is a compact conglomerate, a ground surface of which shows rounded, fine-textured pebbles, ranging in size from 1 millimeter to 1 centimeter and in color from drab and light-red to brown-black. In the specimen and under the microscope none but igneous pebbles occur.

In the microsection the pebbles are mainly andesite lavas with trachytic texture, but they range in character perhaps from andesite to basalt and from transparent to nearly opaque. Originally, they would range also from highly vitreous to holocrystalline and from highly vesicular to compact. In some the magnetite is altered to limonite, in others to (?) hematite; a few retain it unaltered. There is also a pebble of volcanic ash.

The rock is now quite compact. Mostly, the vesicles are filled with a homogeneous chloritic substance which can be called "Chlorite I"; but, when large, they often contain two successive deposits, Chlorite I and Chlorite II (Fig. 12). Chlorite I has differed greatly in its history from Chlorite II. Zeolites seem to be quite absent, and calcite, which fills

fissures, is limited to their neighborhood. The interstices between the well-rounded pebbles are filled with coarsely crystalline chlorite, in plates lying normal to the pebble surfaces. This is identical in character with the Chlorite II of the vesicles; it is yellowish-brown in color and pleochroic, the fast ray across the cleavage having the less absorption; its birefringence (*ca.* 0.014) is a little higher than that of Chlorite I; it has +ve elongation and so is optically negative. It is regarded as negative penninite, secondarily oxidized, which change has raised the birefringence (Fig. 12).

The originally unstable, interstitial glass, abundant in many pebbles, has all been altered. The product is all in the condition of a transparent, birefringent, pleochroic substance, referable to a chlorite. In this it resembles that of KP 312, which was originally a sideromelane tuff. And, as was determined for that tuff, though only after close study, so also here, but much more clearly, it is seen that the substance secondary after glass and the Chlorite I within the vesicles have *practically identical properties*—the same apparent homogeneity, the same color, pleochroism, and birefringence (about 0.012, considerably higher than that of the associated oligoclase); and each has this double refraction uniformly oriented, the fast ray, for example, for each of them being uniformly in the same direction for large areas of the slide and for the most part throughout the rock slice. The color is pale greenish-brown; it is distinctly pleochroic, the absorption being greater for the slow ray, as also in Chlorite II.

From the above it follows that in the trachytic-textured lavas of the slide three materials quite different in origin exhibit systematic orientation of their birefringence: (1) the feldspar crystals arranged by flow, (2) Chlorite I the first and often the sole filling of the vesicles, (3) the chloritic alteration product of the interstitial glass.

The plagioclase feldspars in thin plates extended along the lateral pinacoid have their narrow dimension coinciding very nearly with the axis of vibration for highest refractive index—the slow ray—and therefore the direction of elongation is for the section that of its fast ray. Hence, if the crystals are laid parallel in flow, in a section across them they have uniform orientation for their double refraction. This orientation is common to all the pebbles which have the flow direction in common.

Since both Chlorite I in vesicles and the product after glass are optically alike, it is not always easy to discriminate between them; but the vesicles are better bounded, sometimes contain Chlorite II within Chlorite I, and contain nothing else; whereas the residual glass areas show no tendency to be round, are weakly bounded but are often molded on feldspar crystals, show no trace of zoning, and usually contain other crystals.

In several pebbles the vesicles are elliptical in section; they have, then, a common direction for their elongation, which is also the direction of the slow ray in the Chlorite I which they contain. Thus the directions of extinction and the fast and slow ray do not revolve with the course of the periphery of the vesicle as is usual, and as is the case with an exceptional pebble of greater resistance referred to below. When, as often, the direction of elongation in the vesicles coincides with that of flow texture, the orientation of the birefringence in feldspar is opposed to that in Chlorite I. If the same rock contains also the product after glass, this agrees in character and orientation with Chlorite I.

But the direction of elongation of the vesicles, which carries with it the orientation of birefringence, may make any angle up to 90° with the flow texture; or the vesicles may be so irregular in shape that no systematic direction of elongation is discernible, in which case there is still the systematic orientation of the optical properties.

The original glass had varied in amount in the pebbles between two contrasted modes of occurrence. On the one hand, we have isolated "pools" of glass in an otherwise crystalline rock, and, on the other, the glass formed an all-pervading matrix to the rock. In either case its alteration product, just like the Chlorite I of the vesicles, causes striking phenomena in crossed nicols and especially on addition of the sensitive tint, because it all alike has birefringence which is systematically oriented and is so much higher than that of feldspar as to give a marked contrast in color.

In KP 312, characters like these given above, as well as others, were very obviously related to the nature and direction of the deformation to which the rock had been subjected. This, as was proved by study of the three principal planes at right angles, involved considerable shear. Here, however, there is little evidence of deformation and none of shear; but both the product after glass and the amygdales of Chlorite I have to a large extent in the section a uniform orientation of their length and breadth, the length being, besides, the oscillation direction of the slow, and the breadth that of the fast, ray in them; and in any case they have this uniform optical orientation. So the effects strongly suggest that the cause of the phenomena is to be sought in stress. In the absence, however, of effects of shearing, one may consider whether mere loading would not suffice. And it may be useful if a theory is framed and offered for criticism.

The most important factor would seem to be the physical and chemical character of so much of the material—the relatively basic glass content of so many of the pebbles and their highly vesicular nature. The glass possessed an inherent instability, which under the prevailing conditions led to the immediate factor of greatest consequence—the extremely low resistance against deforming stress of two substances very abundant in the rock. Before this conglomerate was aggregated, the vesicles were already filled with the chloritic substance, probably chlorophaeite, which was to become Chlorite I, for had this change not preceded the aggregation, the interstitial spaces, too, would be filled with Chlorite I instead of Chlorite II. Following the aggregation, palagonitization of the glass in the pebbles would be completed by the action of interstitial water. Both these newly formed substances—"chlorophaeite" and palagonite—were unordered, highly hydrous, impure, chloritic aggregates (as indicated by microscopic characters and what is known of their compositions), with a hardness less than 1, and therefore of great weakness. The conglomerate, therefore, by reason of the large proportion of weak pebbles could yield as a whole under load or other stress, though somewhat irregularly because of the varying resistance of the pebbles—the holocrystalline rocks, indeed, not yielding at all.

During the compression of the rock all cavities were perhaps full of water under pressure. As settlement proceeded slowly, at the rate at which water and the material in it (dissolved under the existing pressure) could be removed from both the palagonite and the chlorophaeite through the pebbles, these chlo-

ritic aggregates were purified, only the insoluble chlorite being left; and favored by the stress conditions they recrystallized into Chlorite I, in the place both of the palagonite and the "chlorophaeite." Crystallizing under stress they were uniformly oriented, as indicated by the uniform orientation of their birefringence, except in so far as variation in the resistance of the pebbles modified the direction of the stress. With the crystallization of Chlorite I the pebbles gained so greatly in resistance that deformation ceased; thereafter Chlorite II grew in the remaining spaces, namely, the interspaces between the pebbles and the centers of those large vesicles which, because of the resistance of the containing rock, had not collapsed. The habit of this Chlorite II (like the fibers of chalcedony in an agate) suggests that it grew in free spaces occupied by solution.

The change of composition from relatively basic glass to chlorite is what can be expected from water action away from air; and the longer the palagonite is subjected to this action, the purer in chlorite composition is it likely to be, chlorite being stable under such conditions.

Its crystallization in place of palagonite can be seen in several sections of Icelandic palagonite tuffs of glacial age and also in those of pre-Cambrian age from Pontesbury Hill, Salop. In some of the latter, indeed, to a large extent it is systematically oriented.

It should be noted that the direction of compression which has affected Chlorite I, both that in the vesicles and that after the glass, is that of the fast ray and agrees therefore with the character of strain in colloids under compressive stress. Some may accordingly claim that a much simpler interpretation is to regard the properties of Chlorite I as merely the effects of strain in the colloids then present—hydrated glass and "chlorophaeite." Against this view are the facts of its agreement in all optical properties with chlorite, and the very high measure of its double refraction, difficult to imagine as retained by a solid so stressed and under the conditions that ensued. For, after the full development of Chlorite I, there grew, in all the free spaces, Chlorite II; and it has been stable apparently ever since, until the present epoch of weathering. If Chlorite I were a colloid of the composition of chlorite and under strain, would it not have gained stability by crystallizing at the same time as Chlorite II?

Phenomena similar to those detailed above have now been noted in six pyroclastic rocks from Jamaica, and it would be interesting to know if they have been recorded from other districts. If the interpretations be correct, the rocks suggest the *evolution of a mineral, a high-grade chlorite, from basaltic and andesitic* glass, and the *evolution* of the same also *from the low-grade chloritic substance* which is deposited as the first layer on the surfaces and in the vesicles reached by cracks in sideromelane or other glassy, relatively basic lava and especially in tuffs of these. For this chloritic substance the term "chlorophaeite" has been used above.

But interesting relations between Chlorite I and Chlorite II are suggested by some of the pebbles. In so heterogeneous a rock it would be surprising if there were no exceptions to the generalizations previously given. Indeed, considering the conditions to which the rock has been subjected, it is surprising that so few exceptions occur. If a traverse is made along the middle of the slice, only two pebbles in ten depart far from the mean optic orientation, and in each case mechanical breaks help to explain the

departure. Exceptions can be attributed (1) to the variety of the rocks represented, (2) to the fact that there was no sand to fill up the interstices between the pebbles, and (3) to a late deformation of the rock, which caused shattering and dislocation, with very abundant veining by calcite.

At one end of the section is a pebble with a largely opaque (limonitic and crystalline) matrix containing plagioclase phenocrysts and vesicles presenting both circular and large irregular outlines. The smaller vesicles are filled with an apparently structureless chloritic material—Chlorite I. The larger within this show also coarsely crystalline chlorite, roughly radial in disposition of the plates—Chlorite II. In these vesicles the radial direction in Chlorite I is the fast ray, but in Chlorite II it is the slow. But where Chlorite I fills a vesicle the *direction* of *compression* in the *rock* is its fast ray! It is as if Chlorite I, filling the small vesicles, obeyed the stress call, but not so the same substance lining the large vesicles still containing solution. The large vesicles thus give an indication of the original disposition of Chlorite I. But, though differing in the disposition of their double refraction, the two chlorites are about the same in color; and in each case the slow ray—radial in Chlorite II, concentric in Chlorite I—is that of greatest absorption, suggesting that they may be identical in pleochroism; both, too (for chlorite), have high double refraction, though that of Chlorite II is a little the higher; and, though Chlorite I is relatively structureless, there is some concentric striation, and a few cracks run around the vesicle through it. Hence the idea suggests itself *that Chlorite I and Chlorite II are closely related; that they have the same optical sign and differ only in position; and that Chlorite I, the first to form, has its vertical axis, c, radial in the vesicle, whereas Chlorite II has the same axis roughly parallel to the boundary.* The relatively homogeneous character of Chlorite I and the coarsely crystalline character of Chlorite II can be referred to different rates of deposit, the chief causative factor being, perhaps, temperature, Chlorite I being that of a higher temperature. This and other physical factors might well determine also the disposition of the crystals—on the base (Chlorite I) or on the faces transverse to this (Chlorite II). Crystallization on the base would lead to a more uniform product than that on other faces, variously inclined as these are to the base: the latter would favor the sheaflike character of Chlorite II. If the above interpretation is correct, an important feature in which the history of this rock differed from that of KP 312 is that it was not compact before it was stressed.

P 357

P 357 also is from the Upper Cretaceous volcanics of the Guy's Hill section but is not more exactly localized. This is a fine-textured, olive-green tuff with fine calcite veins. It exhibits fine-scale spheroidal jointing and breaks down in water. The ordinary method of sectioning therefore fails, but a thin section was obtained by dry grinding.

In *crossed nicols, with the sensitive tint,* it exhibits the same phenomenon as the other rocks here described: *every part* of the slide *on rotation changes in dominant effect from first-order colors to second-order colors;* and this is found to be due to the areas of a rather homogeneous greenish-brown substance. Both compact and vesicular shards are present: all are porphyritic. A vesicular shard contains several vesicles and a crystal of feldspar in a matrix of *chlorite*

with microlites. The vesicles are filled successively with homogeneous "Chlorite I" and with "Chlorite II," showing a faint suggestion of radial structure. They have about the same birefringence, but Chlorite I has its fast ray normal to the surface, whereas Chlorite II has the opposite spatial orientation. The groundmass, originally glass, has double refraction about the same as that of Chlorites I and II; and throughout the fragment has the same uniform orientation as that of the other shards throughout the rock. It is interpreted as chlorite after glass. Its fast ray coincides with the direction of compression in the rock suggested by the structure, and it is slightly pleochroic, the fast ray being that of greater absorption. In this rock, therefore, the characters of Chlorite I, Chlorite II, and of the chlorite after glass agree with those of their counterparts in the last rock described, GH 23.

After a short break which may possibly conceal an unconformity or a fault coarse basic tuffs that weather spheroidally are seen, GH 16 and GH 17, and it is possible that pillow lavas are present among them. These basic pyroclastic rocks are associated with some poorly exposed sediments.[34]

GH 16

One of these, GH 16, has been sectioned and is found to be palagonitic. It is an example of the higher, somewhat more basic tuffs—comes from 22.4 miles, above the horizon of the Cretaceous limestones, and so may be of Eocene age. It is a course, chloritic volcanic tuff of both "vitreous" (now chloritic) and crystalline fragments. Both types of lapilli show abundant flow texture. They are of a more basic character than the rocks previously described, but the petrology does not suggest a different igneous series. Abundant ore grains, both small and large in different fragments, appear to be magnetite. Cavities are filled with optically negative chlorite of rather high birefringence, perhaps −ve penninite altered by oxidation.

Many of the lapilli appear from their characters to have been originally vitreous andesite. These are mostly without vesicles, containing only laths of feldspar and microlites. Their abundant matrix has a refractive index just greater than that of balsam and is *doubly refractive*, the birefringence reaching and even surpassing that of the feldspar. In color it is pale green, clouded with opaque brown, and it is pleochroic, the slow ray being that of greater absorption. Usually the orientation of the birefringence in it is constant within a lapillus; and, where the rock fragment shows flow structure, the orientation in it is usually nearly the opposite from that in the feldspar, the direction of flow being, then, for the matrix the slow ray, whereas for the feldspar it is the fast. There is, however, much variation in the relation between the two. Not infrequently, too, there are two definite directions for the same ray in the matrix of a fragment, irregular wavy bands with one direction occurring within a ground of the other. Most probably the effects are to be attributed to stress in different directions at different times. The characters suggest that this matrix is crystalline and chloritic, as is argued for the other rocks described above. But it is hydrated throughout, and a precedent condition was doubtless "palagonite," using this term in a wide sense for palagonitized glass. Once a glassy tuff, it became palagonitic and is now chloritic.

As detailed above, four clastic volcanic rocks from the road section of Guy's Hill, north of Spanish Town, confirm and extend the conclusions reached from the

[34] Matley and Raw, *op. cit.*, p. 246.

study of that from the road section near Limerick Mountain, north of Kingston. In each district we have submarine vitric tuffs—Eocene and basaltic near Limerick Mountain, Cretaceous and andesitic in the Guy's Hill section; and *in each case the glass is represented by chlorite and is accompanied also by two successive generations of this mineral in the vesicles. The chlorite after glass agrees closely in properties and in orientation with the first deposit of chlorite in the vesicles; both have their present orientation determined by stress. In some cases the two deposits of chlorite in the vesicles agree closely in optical properties, but they appear to differ in position, the vertical crystallographic axis (c) seeming to be radial in the first and peripheral in the second.*

SUMMARY

The deduced stages of development of the rock first described will summarize most of the paper, and they are here tabulated.

STAGES OF DEVELOPMENT OF A PECULIAR CHLORITE-ANALCITE VOLCANIC TUFF, KP 312*

Geologic Events	Development Stages†	Resulting Rocks
Submarine volcanic eruption: Lower Eocene	1. Deposition of coarse, vesicular, sideromelane lapilli; without dust, but containing a few terrestrial, ferruginous lava fragments	Incoherent, marine, vesicular sideromelane tuff
	2. Slight deposition of ferric (oxide or) hydrate (now hematite)	
	3. Coating of fragments and filling or lining of vesicles, with chlorite; commencement of slow palagonitization of sideromelane	Extremely porous, amygdaloidal, sideromelane tuff
	4. Deposition of ferric (oxide or) hydrate (now hematite)	
	5. Filling of all remaining space in and between the sideromelane shards with analcite carrying a little ferric (oxide or) hydrate	Compact, analcite-cemented sideromelane (and palagonite) tuff
	6. Completion of palagonitization of sideromelane (controlled by constancy of volume), separation of finely divided ?anatase	Analcite-cemented palagonite tuff
	7. Decomposition and hydration of olivine	
Local culmination of Antillean orogenesis; Pliocene	8. Deformation of the tuff concentrated in the palagonitized shards, embracing: *a*) Continuous deformation of the palagonite and chlorite, with loss from each: concomitant crystallization of the palagonite into uniformly oriented chlorite, in harmony with that of the flattened vesicles; with regrowth of ?anatase and hematite; albitization of the basic plagioclase of the shards *b*) Cracking and dragging apart of the analcite, with concomitant growth of chlorite (and a little hematite) in all cracks *c*) Redistribution of ferric oxide and spreading of hematite along the shear surfaces	Sheared and albitized, analcite-cemented chloritic tuff
? Thermal action or pressure or both	9. Postdeformation growth of albite after analcite (probably extensions of the albite crystals in the shards)	The same, modified by some albitization of analcite

* Collected by Dr. C. A. Matley from the top of the Purple conglomerate or Wagwater group, referred to Lower Eocene. Locality near Newcastle, Jamaica, on Buff Bay Road, at 23¼ miles from Kingston.

† Stages 1–5 were probably rapid; Stages 6 and 7, slow; Stage 8, rapid; and Stage 9, slow.

The rock's special interest arises from the detail in which it exhibits its history and from the instructive comparisons which it offers with palagonite tuffs from the Pacific and from Iceland.

The extensive range of its determinable development is attributable mainly to three factors: first, the inherent instability of sideromelane; second, the extreme weakness of palagonite with a hardness (in its natural subterranean condition) well below 1 of Mohs's scale; and, third, the very low grade of dynamometamorphism. The first extends over Stages 1–6: the other two conspire to give us the complicated Stage 8 without obliterating the earlier stages, and this notwithstanding that surrounding rocks exhibit little deformation.

The rock appears to be unique among described tuffs by reason of the high proportion of analcite, which, despite some subsequent alteration to albite, still constitutes 43 per cent of the rock. This mineral is here attributed mainly to reaction between the salt of the sea and silicates, especially volcanic dust under moderate volcanic heat. The rock is of interest also in that it suggests a mode of origin for chlorite schist and especially for albitic chlorite schist. For these palagonitization may very often have been an essential stage.

Study of this and of palagonite tuffs indicates that palagonitization involves the formation of chlorite from basic volcanic glass; and that deformation, when it occurs, involves a further evolution of this chlorite, as well as of the chloritic substance forming the first deposits in the vesicles, from a low to a high grade, the two at the same time converging until they are practically identical in optical character and so also probably in chemical composition.

That this is the case is strongly supported by the characters of several other Jamaican pyroclastic rocks, originally largely vitreous. For in these the substance after glass is transparent and hence exhibits quite clearly its optical properties; and in two of them three chlorites—"Chlorites I and II" in the vesicles and the chlorite after glass—originating in the rock at different times, are closely similar in their optical properties, though Chlorite II, it is suggested, differs from the others in its crystalline orientation.

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FRICTION CRACKS AND THE DIRECTION OF GLACIAL MOVEMENT

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ABSTRACT

This is a study of glacial crescentic markings, attempting to establish a correlation between the orientation of these features and the direction of ice movement. The principal crescentic marks are reviewed. It is observed that the fracture of these features dips forward in the direction of the ice movement and hence may be a usable criterion in determining the direction of ice movement. The term "friction crack" is suggested for glacial crescentic markings which possess this feature.

INTRODUCTION

Glacial crescentic markings have been described in detail by T. C. Chamberlin,[1] G. K. Gilbert,[2] and F. H. Lahee.[3] Five or six types are described and differentiated, though no especial effort is made to relate their orientations to the direction of ice movement. Figures 1 and 3 illustrate some of these types and one other observed by the writer. Unfortunately, subsequent workers failed to differentiate between the markings, and the term "chattermark" has come to include all glacial crescentic marks, even though chattermark is the term applied by the early workers to one specific type of mark. The oft-heard statement that chattermarks point the direction of ice movement is true in the strict sense but not in the loose sense of general usage. The difficulties which arose from the abuse of the term are obvious on examination of the several crescentic markings; the horns of different types point in opposite directions. Therefore a criterion —other than the orientation of the horns —was sought which would make glacial crescentic marks more useful in determining the direction of ice movement. Some simple experiments suggested that the forward dip of the principal fractures of certain of the crescentic marks might be diagnostic. Literature and field work showed not only that such marks are common on glaciated rock surfaces but that the dip of the fracture is a reliable criterion; the horns alone are not.

A new term distinct from the names of crescentic markings is desirable in order to avoid more confusion. "Friction crack" has been chosen because the fracture (crack) was formed by a local increase in friction between the overriding ice and the bedrock.

FRICTION CRACKS

Friction cracks were observed on nearly every glaciated bedrock surface examined during the course of the study. Generally they occur in series with the axis parallel to striae and the direction of ice movement, but the individual cracks (fractures) are oriented at right angles to striae (Figs. 1 and 3). Friction cracks are generally deeper than striae and hence outlast the latter. They occur in many places where weathering has completely

[1] "The Rock Scorings of the Great Ice Invasions," *U.S. Geol. Surv. 7th Ann. Rept.* (1885), pp. 218–24.

[2] "Crescentic Gouges on Glaciated Surfaces," *Bull. Geol. Soc. Amer.*, Vol. XVII (1906), pp. 303–16.

[3] "Crescentic Fractures of Glacial Origin," *Amer. Jour. Sci.*, Vol. XXXIII (4th ser., 1912), pp. 41–44.

obliterated the striae—heretofore the most commonly used criterion to determine the direction of ice movement.

Friction cracks do not have one simple form but are those glacial crescentic markings which possess a distinct fracture which dips forward into the rock. The two most common crescentic markings—the *crescentic gouge* and *crescentic fracture*—possess this fracture and hence are friction cracks by definition. These features have been observed on all rock types: quartzite, limestone, diabase, shales (even badly fractured shales), coarse sandstone, and coarse-grained granite. Crescentic gouges are more common on certain rocks, crescentic fractures on others. However, differentiation of the crescentic markings is not necessary if the direction of dip of the fracture can be determined.

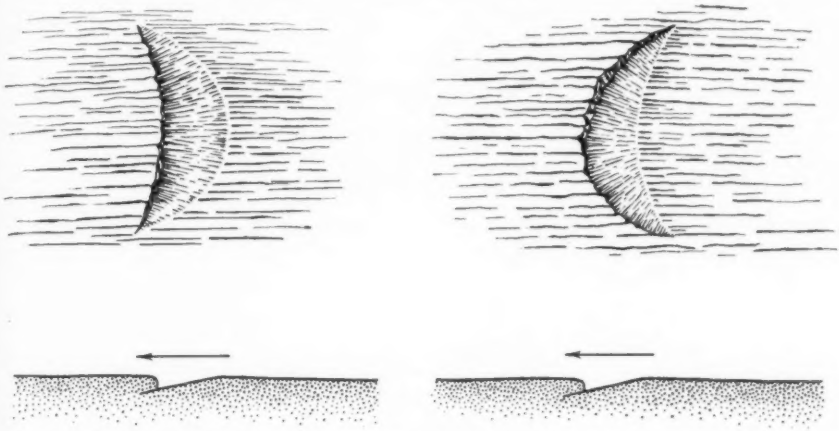

FIG. 1.—Diagrammatic representation of (*right*) crescentic gouge and (*left*) lunate fracture showing the horns pointing in opposite directions but the fracture dipping in the direction of movement of the ice in both cases.

DESCRIPTION AND ORIGIN

The *crescentic gouge* is the result of two fractures. The principal fracture dips forward obliquely at a low angle, producing a smooth surface, convex upward. Terminating against it is a ragged, nearly vertical fracture. This secondary fracture is concave backward and gives the backward-pointing orientation of the horns of the feature (Fig. 1, *right*).

The principal fracture is the friction crack. Its exposed surface allows easy identification of the direction of dip of the fracture.

Crescentic gouges occur in rows. The number of fractures per row is generally less than is the case in rows of crescentic fractures; indeed, a single crescentic gouge not directly associated with others is not uncommon. A single crescentic gouge is oriented transverse to the direction of ice movement, but the axis of a series is parallel to it. There is considerable variation in size from less than an inch to more than 6 feet between the horns, although gouges more than a foot across do not appear to be common. Gilbert[4] reports that in some rows the gouges are progressively larger. Generally, however, gouges are of uniform size in a given series. The shape of the crescen-

[4] *Op. cit.*, p. 305.

tic gouge varies considerably. A truly crescentic shape is rarely observed, for the shape depends on the way the fragment breaks out. The gouge sometimes appears as a double crescent. Crescentic gouges occur on all types of rock but are best developed on brittle rocks. Some types on which these glacial markings have been found are: massive sandstone (T. C. Chamberlin, the writer); granite (Gilbert); shale (the writer); limestone (the writer); quartzite (Lahee, the writer). Topographically they are most abundant near the crests of hills on the stoss side.

Gilbert's theory[5] to explain the origin of crescentic gouges has been uncontested since it was presented in 1906. It is based on the conoid of percussion and the conchoidal fracture obtained by applied pressure on substances such as obsidian or flint. Figure 2 illustrates three types of conchoidal fracture: *A* is a percussion cone obtained by a vertical blow on glass; *B* illustrates the conchoidal fracture produced by applied pressure; *C* shows the fracture which might be expected if pressure were exerted obliquely.

Ice moving over bedrock would exert a force oblique to the surface as shown in *C*. Differential friction and pressure necessary to the formation of crescentic gouges would be produced by a boulder held in the bottom of the ice, since it would concentrate pressure on the place where it made contact with the bedrock. Direct contact with the bedrock would produce grooves not generally found associated with crescentic gouges; but direct contact is not necessary to the formation of fractures. Gilbert's hypothesis is that a boulder is pressed into the rock by the weight of ice, and because of the rock's elasticity a ridge is bowed up around the point of concentrated pressure (Fig. 2). The moving ice continues to force the boulder forward and downward until finally the elastic limit of the rock is reached and fracturing occurs in front of the boulder. This fracture should be conchoidal and asymmetrical forward, as is actually the case in the crescentic gouge. The wedge of rock formed by the fracture is then caught and broken off by the ice or boulder, leaving the crescentic gouge. The deepest depression in the crescentic gouge is found at the center, where the fracture is greatest. Rhythmic repetition of these conditions produces a series of gouges.

Lunoid furrows were described by C. T. Jackson, G. L. Vose, C. H. Hitchcock, and A. S. Packard, Jr., in New England. Packard[6] in 1868 said they are "crescentic-shaped depressions in the rock with the concavity toward the north" occurring in series of four or five. Their origin is ascribed to the gouging effect of boulders held in the bottom of the ice as it moved forward and then contracted. T. C. Chamberlin noted that Dr. Packard's hypothesis of their origin is based on a misapprehension of glacial movement.[7] It seems probable, as Gilbert[8] says, that lunoid furrows are identical with the crescentic gouge.

The "jagged groove" of Chamberlin is a groove with relatively large fractures running transversely across it at intervals as shown in the upper diagram of Figure 3. The fractures extend beyond the walls of the groove and have all the characteristics of a series of crescentic gouges except for the groove extending along the axis. The surface of the principal fracture is well exposed and dips obliquely forward as in all other friction

[5] *Ibid.*, pp. 307–11.

[6] "Ice Marks and Ancient Glaciers in the White Mountains," *Amer. Naturalist*, Vol. I (1868), p. 256.

[7] *Op. cit.*, p. 223.

[8] *Op. cit.*, p. 314.

cracks. Its characteristics are very different from those of the true chattermarks described on page 250, though the two might possibly be confused.

tion of ice movement and has a smooth, rounded surface, convex side upward. In this case, however, the fragment has been broken out in such a manner that the

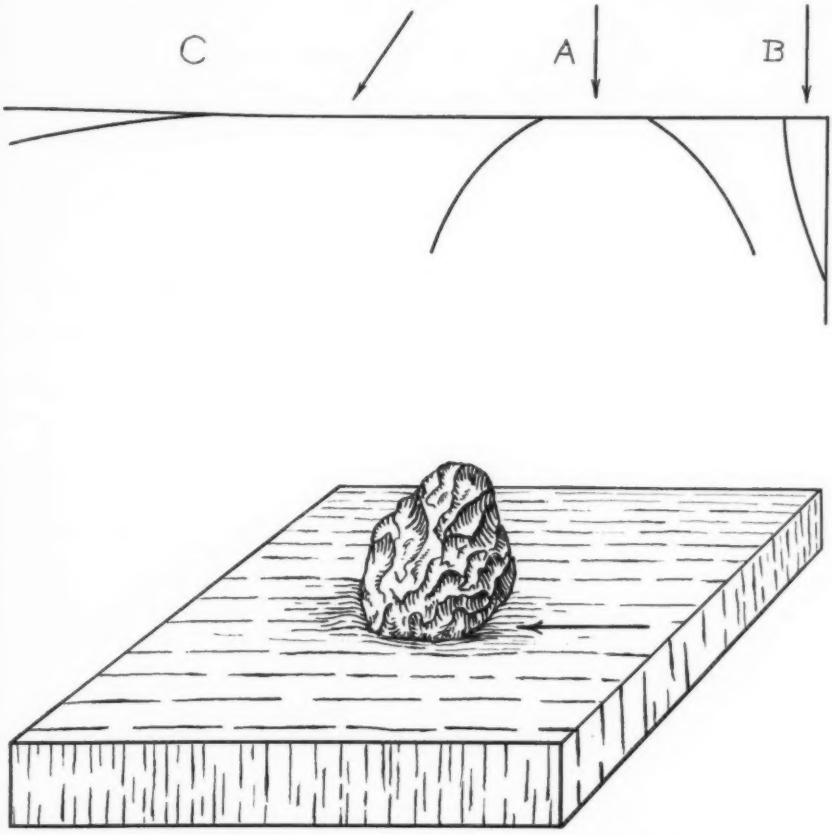

FIG. 2.—*Upper*, types of conoidal fractures produced in brittle rocks (after Gilbert). *Lower*, ridge bowed up in bedrock in front of a boulder held in the base of a moving glacier.

Lunate fractures (Fig. 1, *left*) are a third type of friction crack. This mark is very similar in appearance to the crescentic gouge. It has not been described before in the literature but was twice observed by the writer in the field. As in the crescentic gouge, the principal fracture dips obliquely forward in the direction of ice movement and has a smooth, rounded surface, convex side upward. In this case, however, the fragment has been broken out in such a manner that the vertical fracture is concave forward instead of convex forward; the horns thus point in the direction of ice movement—the exact opposite from the crescentic gouge.

These crescentic markings have been found by the writer on sandstone and shale closely associated with crescentic

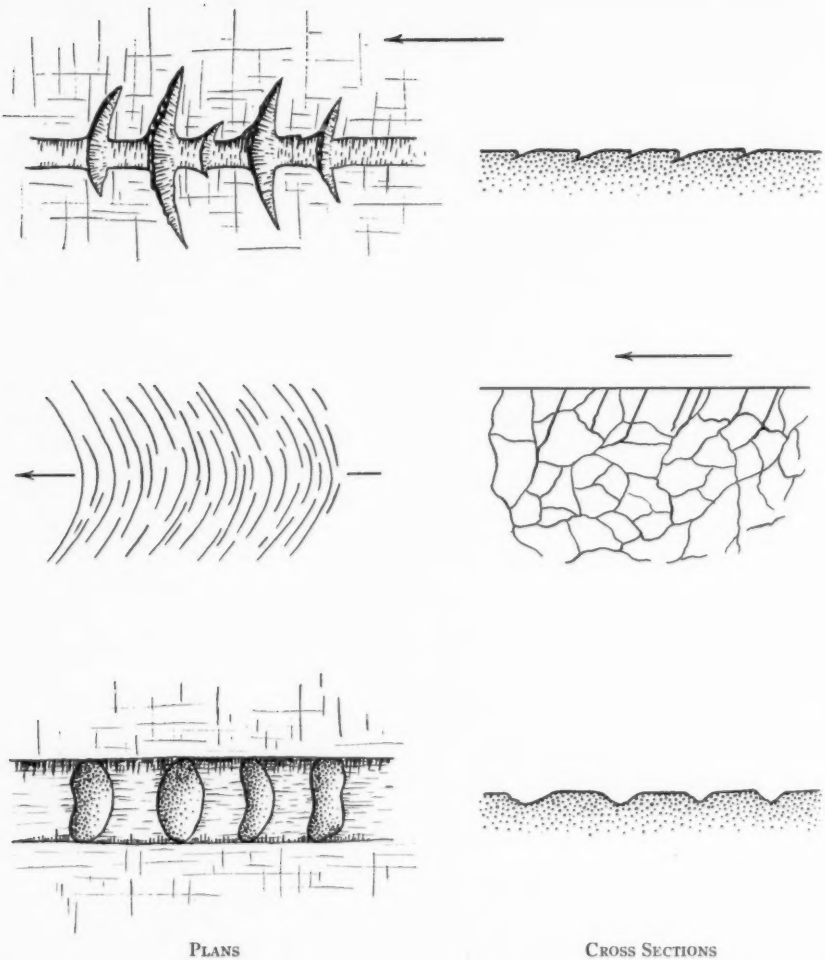

Fig. 3.—Three crescentic markings: *upper diagrammatic representation*, jagged groove similar to a series of crescentic gouges but with a groove down the axis; *middle*, the crescentic fracture is one of the most common friction cracks, but no chip has been removed from this marking whose horns point forward; *lower*, the chattermark commonly is not crescentic and has no principal fracture, hence is not a friction crack.

gouges. It seems likely that their mode of origin is similar to that of crescentic gouges. In this case the fragment simply broke out in such a way as to leave a secondary fracture curved concavely forward rather than convexly forward.

Crescentic fractures, called "crescentic cracks" by some authors, are superficial curved fractures. The fracture is transverse to the striae and concave forward, that is, the horns point in the direction of ice movement—the exact opposite from the orientation of the horns of the crescentic gouge. They generally occur in rows of a few score paralleling the striae. The length of the individual fractures varies from less than an inch to about 7 inches from tip to tip. Variation in size is common in a single row, but as a rule they center along a common axis or even a groove, although this is by no means always the case. At the extremities of the larger fractures there is commonly a small fracture just to the rear (Fig. 3, *middle diagram*). The shape of the fractures is hyperbolic rather than truly crescentic.

The fracture (this is the friction crack) dips forward at an angle of 60°–80° and extends downward from $\frac{1}{16}$ to 1 inch; generally it is about $\frac{1}{4}$ inch deep. Near the axis the fracture is clear cut and passes directly through the grains of the rock; toward the extremities, both horizontally and vertically, the fracture tends to wander between the clasts or crystals. In crescentic fractures there is but one fracture; no chip has been removed[9] as in the case of the crescentic gouge. This fact often makes the determination of the direction of the dip of the fracture somewhat difficult. A piece of paper may be inserted in the crack in some cases, or a light-colored halo within the concavity, especially in quartzite, may indicate the direction of dip.

This type of fracture has been found on many kinds of rock: quartzite (Lahee, Winchell, the writer); granite (Andrews, the writer); limestone (Chamberlin); shale (the writer); diabase (the writer). Crescentic markings are best developed in hard, brittle rocks. Quartzite appears to take and retain these marks better than any other rock in which they have been observed by the writer. Crescentic fractures occur most commonly on the stoss side of a hill, especially near the crest, but are not uncommon on the lee slope.

Gilbert[10] suggests that crescentic fractures are the result of local increase in friction between the overriding ice and the bedrock. The moving glacier would tend to pull the bedrock with it, so that any point of greater friction would be moved forward in respect to the surrounding rock. When the tensile strength of the rock is exceeded, a tension fracture results.

The rock is subjected to both compressional and tensional forces, as shown diagrammatically in Figure 4. Since rock fails more readily under tension than under compression, a tension fracture will result. The rhythmic building-up of stress to the point of relief by fracture produces the series of fractures characteristic of this type of marking.

It was Gilbert's belief that stones, or even a pocket of sand held in the bottom of the ice, would produce the necessary local increase in friction. Actual contact between the agent and the rock surface is not requisite. This would explain the lack of striae down the axis of a row of fractures. Lahee[11] made a more compre-

[9] Rarely a chip has been removed to expose the fracture surface. See p. 254.

[10] *Op. cit.*, pp. 307–8.

[11] *Op. cit.*, pp. 41–44.

hensive study of crescentic fractures than did Gilbert. He agrees that tension was the disruptive force and that contact between the agent and the rock surface is unnecessary to the formation of the fracture. He disagrees, however, over the character of the tool which produced the fractures. He believes it to have been pointed rather than simply a pocket of sand. His reasons are, briefly, the following:[12]

1. The number of fractures increases toward the axis.
2. The fractures are most sharp at the axis, less so at the extremities where they tend to wander between clasts.
3. Striae or grooves are frequently in intimate association with a series of fractures.
4. The curved fractures are hyperbolic, showing a local concentration of force.

Chattermarks are chipped-out depressions ordinarily occurring at regular intervals within a groove (Fig. 3, *lower diagram*). There is no true fracture, as in the crescentic fracture, but simply a forward and a backward slope. There seems to be a general tendency toward a crescentic shape with the horns pointing forward, but frequently the marks are oval-shaped. Where chattermarks are found they always occur within large striae or grooves, and their size is usually limited by the width of the groove in which they appear.

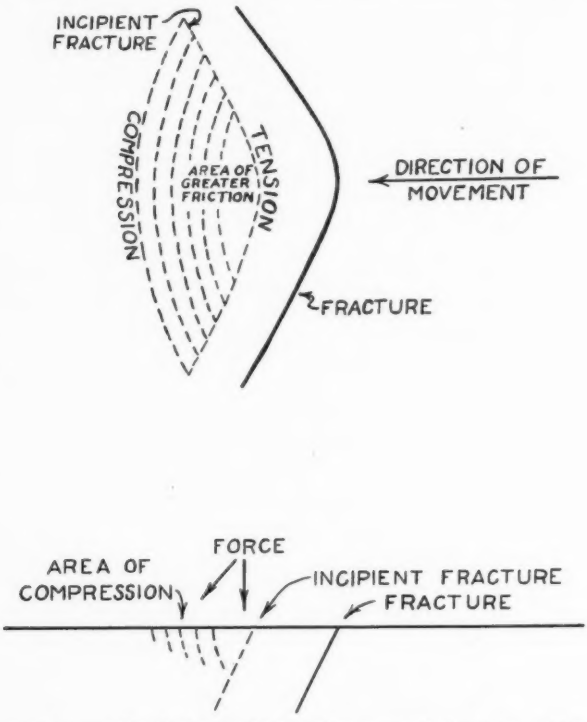

FIG. 4.—Diagrams representing the forces which produce crescentic fractures: *upper*, plan; *lower*, cross section.

[12] *Ibid.*, p. 43.

The origin of these depressions is much the same as that of the chattermarks familiar to machinists. A stone or a boulder held in the bottom of the moving ice plowed a furrow in the bedrock. When the elastic limit of the rock was exceeded, shattering resulted. Any roughness or differences in hardness of the surface would intensify this shattering effect. Vibration caused by the proper relationship between speed of movement and pressure exerted, plus the elasticity of the bedrock and the glacier, would result in rhythmic formation of chatters. This vibratory motion might be compared with the familiar phenomenon produced when chalk is run across a blackboard to produce chattering.

Chattermarks are generally found in brittle rocks such as limestone, granite, massive sandstone, or diabase. None has been reported on shale. Like other glacial scorings, they are most common on the stoss side of hills but are also found on the lee side.

Chattermarks are not friction cracks, since they do not possess a usable fracture.

EXPERIMENTS

Certain simple experiments were carried out with the hope of reproducing crescentic markings, of determining their mode of origin, and especially of finding some general criterion for their use in determining the direction of glacial movement.

In none of the experiments was there any attempt to reproduce conditions to scale in considering such factors as time, pressure, hardness, and character of material and tool. The idea was simply to produce crescentic markings on various substances and to study their characteristics and mode of formation.

As Gilbert mentioned using gelatin in his study of crescentic gouges, this substance was first tried. All efforts to reproduce "crescentic gouges"[13] were unsuccessful. The elasticity of the gelatin was such that the material failed under tension and produced "crescentic fractures" instead of "crescentic gouges." The size of the "crescentic fractures" depended on the area of contact between the tool and the surface; the greater the surface of contact the larger the fracture. As Lahee had found at Northey Hill,[14] these crescentic fractures were really hyperbolic rather than crescentic in shape. The dip of the fractures was invariably forward, that is, in the direction of movement of the agent. There appeared to be very little difference in results whether the tool was pointed or blunt, except that a sharper instrument tended to dig into the surface and disrupt the gelatin. The character of the gelatin is certainly very different from rock, yet the form of these "crescentic fractures" compares favorably with any of those described in the literature or observed in the field.

It was found that chattermarks can be made on many substances, such as paraffin, wax, wood, tar, metals, and even blotting paper. The tools can be as varied in size, shape, and hardness. Chattermarks are deeper gouges made within striae or grooves. They are a vibratory phenomenon and occur when the speed and applied pressure are properly adjusted. Chatters can be produced on smooth surfaces, but any roughness, unevenness of texture, or differences in hardness will intensify the chattering. The size of the marks is determined by the width of the groove in which they occur. Their shape is partly dependent on the shape of the instrument, partly on

[13] In this paper, markings produced in the laboratory which resemble those seen on glaciated surfaces are enclosed in quotation marks.

[14] *Op. cit.*, p. 42.

the speed of movement and the degree of pressure exerted. There seems to be a general tendency toward a crescentic shape with the horns pointing forward, but in some cases the features are oval or irregular. There is no fracture—hence it is not a friction crack—in this mark as there is in the crescentic gouge and crescentic fracture. Rather there are two "slopes." Most commonly the forward slope is less steep than the backward slope. These features are shown especially well in paraffin, and almost any instrument which is not too sharp may be used for a tool. This substance, however, is not brittle enough to form either crescentic gouges or crescentic fractures.

In the formation of crescentic fractures the most successful results were obtained in glass. The instruments used were a knife, a file, and a wrought-iron nail. Quartz was found to be too hard a tool, and it merely scratched; while soft materials left no mark at all. The tools had to be somewhat pointed; blunt instruments were quite ineffective, though a greater pressure might have produced fractures.

A file or knife pushed across glass with sufficient pressure produced "crescentic fractures." These were always small (about $\frac{1}{32}$ inch across) and curved, with the horns pointing in the direction of movement of the instrument. They were semicircular rather than hyperbolic, as was the case when the mark was made in gelatin. The fracture was very shallow and dipped slightly forward. The mechanics of its formation is taken to be the same as that described by Lahee (see pp. 249 and 250) for crescentic fractures in quartzite.

The "crescentic gouge" was also made in glass. A sharper tool and more pressure were necessary to produce these marks than to produce "crescentic fractures." The fracture was more pronounced near the axis than at the extremities and dipped forward at an oblique angle. The fracture of the "crescentic gouge" started at a point on the surface and extended downward with a conoid shape such as that described above for the crescentic gouge.

The idea that the dip of the fracture in certain of the crescentic markings might be the desired criterion for determining direction of ice movement came as a direct result of these experiments, since the fractures invariably dipped in the direction of movement of the instrument.

LOCALITIES WHERE FRICTION CRACKS WERE STUDIED

Friction cracks were observed and studied over a wide area in northeastern United States. The principal localities were in the vicinity of Hanover, New Hampshire; the Palisades region, New Jersey; and along the Delaware River from the Delaware Water Gap to Port Jervis.

Mount Cube, New Hampshire.—Mount Cube is situated in western New Hampshire, about 8 miles northeast of Thetford, Vermont. The resistant quartzite of the Clough formation[15] causes it to stand 1,500 feet above the surrounding country. The character of the rock is such that it took and has held glacial markings exceedingly well. Today most of the exposed bedrock near the crest of the mountain is glacially polished, and striae, grooves, and friction cracks are abundant.

The northern side of *roches moutonnées*, and of the mountain itself, has been glacially scored, while most of the southward-facing exposures have been severely plucked. Furthermore, all striae and rows

[15] Hadley and Chapman, "Geology of Mt. Cube and Mascoma Quads. N. H." (1939), map.

of crescentic markings are oriented in a north-south direction. There can be no doubt that the ice movement was approximately toward the south.

Friction cracks in the form of crescentic fractures and crescentic gouges were found in abundance on the crest of the mountain. The cracks dip southward in the direction of ice movement in every case where the dip could be determined. For the crescentic gouges the dip of the primary fractures is clearly visible. Many of the gouges show that the oblique friction crack extends beyond the vertical fracture. The ordinary color of the rock is light gray, but in many cases there is a white crescent (showing air space) extending in front of the gouge. The secondary fracture is crescentic in shape, causing the horns to point backward. On Mount Cube the crescentic gouges vary in size from $\frac{1}{2}$ inch to about 1 foot across. They occur singly, in pairs, or in rows of a dozen or more. They are similar to those described by Gilbert, although his markings were in granite of the Sierra Nevada Range, while these are in quartzite. It might also be noted that the crescentic gouges of the Sierra Nevada were made by mountain glaciers, while these were produced by continental glaciation which completely overrode Mount Cube.

The direction of dip of the crescentic fractures is not so easy to determine as in the case of the crescentic gouges. The crescentic fracture has only one steeply dipping fracture, so that no chip has been removed to expose the surface of the crack. The best method of establishing the direction of dip of this friction crack is to find a row of cracks which has been broken along the axis. In other cases it is possible to insert a piece of paper along a friction crack and thus obtain the direction of dip. The crescentic fractures on Mount Cube occur in rows of from 10 to 50 cracks. In some places the fractures are found within a groove or with a stria running down the axis; in others they occur alone. The horns point uniformly in the direction of ice movement. In every way these marks correlate with those of Lahee at Northey Hill.

No other type of crescentic markings was observed on the quartzite of Mount Cube. The dip of the friction cracks is forward in every case observed, giving support to the theory advanced.

Northwestern New Jersey.—The Appalachian Valley and Ridge physiographic province extends across northwestern New Jersey from the Delaware Water Gap to Port Jervis. The dominating feature is Kittatinny Mountain, which stands high because of its quartzite summit. The High Falls sandstone forms the foothills on the northwest and the Martinsburg shale the foothills on the southeast. The whole region has been glaciated. R. D. Salisbury[16] showed the general direction of the ice movement to be southwest, following the topography; however, in the northern part there was a westerly movement across the ridge, while in the southern section the ice moved southward across the mountain. All these trends were observed in field work in this area by the writer.

In High Point State Park near Port Jervis resistant Tuscarora quartzite is exposed over much of the crest of the mountain. There has been some plucking by the glaciers, and much of the surface has been weathered since the retreat of the glaciers. Nevertheless large areas of exposed bedrock are beautifully polished. Striae are indistinct in many places either because the quartzite was so resistant to the scoring effect of the glacier or because weathering has obliterated them. The

[16] "The Glacial Geology of New Jersey," *Geol. Surv. New Jersey*, Vol. V (1902), glacial map.

outstanding glacial markings are the rows of friction cracks (almost entirely crescentic fractures). Each series extends for several feet, even several yards. They run parallel to each other and are sometimes so close together that the extremities of the cracks overlap. On every polished surface examined along the road running north from the highway to the monument these friction cracks were observed. The horns of the friction cracks invariably point in a westerly direction. They range in size from 1 to 4 inches across. The direction of dip is not everywhere apparent, because no chip has been removed to expose the surface of the friction crack. However, the dip of the fracture is forward toward the concave side of the mark. At one spot near the retaining wall 75 yards north of the monument, frost action has broken the rock down the axis of a row of friction cracks (crescentic fractures), giving an excellent vertical cross section. A few measurements showed the dip of the fracture to be approximately 35° W. However, the rock surface slopes about 20° to the east, so that the actual angle the fracture makes with the surface is 55°. The fractures extend downward for as much as an inch and in some cases even deeper. This checks with the findings of Lahee at Northey Hill. Most of the striae have been removed by frost action, yet the rows of friction cracks still show up clearly and may be used in determining the direction of ice movement.

Crescentic gouges, however, are not very numerous in this locality. On some surfaces none could be found at all. At the observation platform nearest the highway, a few gouges may be seen. No really good series was observed, although three or four in a row were seen. The dip of the principal fracture is westward.

On the crest of Kittatinny Mountain, northeast of the fire tower located due south of Millbrook, weathering and lichens have obliterated most of the polished surfaces. Striae are very indistinct. Nevertheless, three series of friction cracks are clearly seen oriented S. 56° W., with their horns pointing in that direction. The dip of the principal fracture of two crescentic gouges was clearly toward the southwest. From these facts the movement of the ice was determined to be S. 56° W., paralleling the ridge. A later check with Salisbury's map[17] showed this to be nearly the same as his trend line.

One mile east of Flatbrookville, on the dirt road between that town and Newton, there are several excellent glaciated surfaces on the High Falls sandstone. For about ½ mile along the top of the hill these scorings are well preserved in fine-grained red sandstone. There are several sets of striae all trending west of south. Paralleling the striae are rows of chattermarks and friction cracks.

The friction cracks occur in series of four or five and are of two types—crescentic gouges and lunate fractures; no crescentic fractures are present. The dip of the fracture of both types is toward the south. The crescentic gouges are typical —the surface of the oblique fracture is exposed by removal of the rock fragment —and the horns point backward. Some series of crescentic gouges were joined by a groove down the axis; these are Chamberlin's jagged grooves. It was at this place that the writer first observed the friction crack which he has named "lunate fracture." Actually it is quite similar in appearance to the crescentic gouge, but the orientation of the horns, caused by the crescentic-shaped vertical fracture, point forward instead of backward. The

[17] *Ibid.*

really significant feature is that the fracture dips forward in the direction of ice movement as it does in every crescentic marking possessing a well-developed fracture.

A complicating factor in this rock is a tectonic fracture which might have modified the direction of fracture caused by glacial action. The two fractures could be clearly distinguished, however, and the glacial fracture is apparently completely independent of the older rock fracture.

The dip slope of a hogback 2 miles south of Port Jervis and immediately behind Rock View House has been beautifully polished by glacial action. The 25° slope faces the Delaware River and forms the eastern margin of the flood plain. Part of the glaciated surface of the Esopus shale bedrock has scaled off to a depth of about an inch (no glacial fractures have penetrated to that depth), but the remaining surfaces contain abundant scorings.

Rows of friction cracks parallel the striae trending S. 75° W. Crescentic gouges and crescentic fractures are abundant. The crescentic fractures are from $\frac{1}{2}$ to 4 inches across from horn to horn. Vertical cross sections of these marks can be seen in several places. The fractures dip forward at rather steep angles. The length of the rows of crescentic fractures varies considerably, as does the number of individual fractures occurring in a single row. Fifteen were counted in one series, 29 in another. Two series of crescentic fractures, 5 well-developed crescentic gouges, and many striae occupy an area of about 3 square feet. The crescentic gouges are larger than crescentic fractures and are in every way characteristic, with fracture dipping forward and the horns pointing backward.

DIABASE DIKE

There is an excellent exposure of a glaciated diabase surface on New Jersey State Highway No. 4, $\frac{1}{2}$ mile east of Hackensack. The scorings occur on a hillside which slopes rather steeply toward the west. Striae point S. 4° W., extending obliquely uphill. The rock is fine-grained diabase, and the joints are so far apart that previous rock fracture seems to have no effect on glacial fractures.

Several rows of well-developed crescentic gouges parallel the striae. The principal fracture dips forward and extends below the vertical fracture. The latter is curved, with the horns pointing backwards. Individually, the size of the marks ranges from $\frac{3}{4}$ to 3 inches. As is commonly the case, many of these fractures are not actually crescentic, but the general tendency is such.

Series of crescentic fractures are found scattered over the surface of the diabase outcrop. They are parallel to the striae and the rows of crescentic gouges; their horns point forward in every case. These fractures are not so well developed as are crescentic fractures in quartzite. They are more superficial and less sharp, as the fracture does not extend far below the surface. The dip of the friction crack is forward, though it was not easy to determine. An average of 15–25 fractures occur in a single series, and a whole row is less than 1 foot long. These friction cracks are about 1 inch across and of uniform width in each set. Striae are intimately related to the crescentic fractures. Generally they run along the axis of the fractures but are not deep.

Chattermarks are found in many of the larger striae and furrows but are of little value in determining the direction of ice movement. They occur in series, and their size depends on the width of the furrow. The marks are usually longer

across the axis of the furrow than parallel to it. Often the shape is somewhat crescentic, with the horns pointing forward, but frequently they are oval or nearly circular. These chattermarks might be described simply as nicks, generally recurring rhythmically in a furrow. The sides of the depression are rounded, not angular as in the case of crescentic gouges, and there is no single sharply defined fracture surface.

WEST OF PORT JERVIS, NEW YORK

In its upper course the Delaware River flows a winding southwesterly course in a narrow gorge across the Appalachian Plateau. At Port Jervis, at the conjunction of New York, New Jersey, and Pennsylvania, it enters the Valley and Ridge Province, takes a right-angle turn to the southwest, and flows for 50 miles in that direction along a subsequent valley. This valley extends also to the northeast from Port Jervis, paralleling the commanding Kittatinny Ridge.

From the reports of I. C. White[18] and Salisbury[19] it is evident that the regional movement of the ice was southwesterly over the eastern part of the plateau, as it was in the Valley and Ridge Province. There is some disagreement in their maps, however, as to the general trend along the Delaware River from Port Jervis to the Delaware Water Gap. Salisbury indicates a more westerly trend in ice movement and shows considerable modification by local topography. Though White did recognize that local topography is effective in directing ice movement, the trend lines on his map indicate that he did not possess enough striae directions to show local modifications.

[18] "The Geology of Pike and Monroe Counties," *2d Geol. Surv. of Pa., Report of Progress G6* (1881), map.

[19] *Op. cit.*, map.

Immediately west of Port Jervis in a road cut on Point Peter there are excellent glaciated surfaces on Hamilton shale. These occur on the bedding planes of the rock, which dips 18° NW. and has a strike of N. 62° E. The orientation of the striae ranges from N. 62° W.–S. 62° E. to N. 45° W.–S. 45° E. Friction cracks were found in series of from 6 to 10 in many grooves running parallel to the striae. The dip of the fractures is to the northwest. The Hamilton shale has a fracture cleavage which may have interfered with the orientation of the glacial fractures. At Point Peter the cleavage dips only slightly more than the bedding planes, and at about the same angle as the friction cracks. It may be that the orientation of the cracks was determined by the pre-existing cleavage.

Four miles upriver along the highway near Hawk's Nest other polished surfaces were found. They occur on the north side of the river, where there is a steep cliff both above and below the road. The glaciated surface is the bedding plane of a light-gray sandstone which dips northwest at a low angle. The striae are oriented N. 45° W.–S. 45° E. Rows of friction cracks, both crescentic gouges and lunate fractures, parallel the striae. The friction cracks dip to the northwest.

The dip of the friction cracks indicated that the ice moved northwest, that is, upriver. Efforts have been made to determine the direction of ice movement from other evidence, but, unfortunately, this is not conclusive.

The course of this portion of the Delaware River is at right angles to the regional trend of ice movement as worked out by Kümmel, Salisbury, Lesley, and White. The map of the first two geologists[20] indicates the sensitivity of the ice to local topography, but, unfortunately,

[20] Salisbury, *ibid.*

their map does not extend west of Port Jervis. Nor is there any mention of direction of movement in that part of the Delaware Valley in the text. Lesley's[21] map shows no deflection in this valley, and no striae are recorded in this area. It seems certain that a gorge of this size would have modified the direction of ice movement. The striae and rows of friction cracks in the valley do actually run at right angles to the regional direction of ice movement and along the river valley. The question is whether the ice moved northwest or southeast. The following is a summary of the evidence supporting each possibility.

FOR SOUTHEAST MOVEMENT

1. Jointing may account for the northwest dip of the friction cracks found in this valley.

2. The glaciated surfaces slope to the northwest, and glacial scorings are best developed on the upgrade.

3. Though ice moved westward across Kittatinny Mountain at High Point, south of Port Jervis, it is plausible that the scorings were made at a later date, during the waning stages of glacier occupation. At that time Kittatinny Mountain must have been a controlling factor in ice movement.

4. The trend of regional ice movement was southwesterly, paralleling the broad Neversink Valley and Kittatinny Mountain just to the southeast. The Delaware Valley extends southeast directly across that regional movement and joins the Neversink at right angles. It would seem logical that ice might be deflected by the Delaware Valley and turned southeastward into the Neversink; a northward deflection might appear improbable.

[21] White, "Pike and Monroe Counties," *Pa. 2d Geol. Surv. G6* (1881), map.

FOR NORTHWEST MOVEMENT

1. It has been found in all places where the direction of ice movement is known that the dip of friction cracks is invariably in the direction of ice movement. At Point Peter, admittedly, preexisting rock fracture may have reversed the dip of the glacial fractures. However, there are friction cracks near Hawk's Nest which dip to the northwest.

2. White[22] reports Oneida (Tuscarora) conglomerate boulders due west of Port Jervis at altitudes up to 1,475 feet. These are scattered on the hills 10–12 miles northwest of the Delaware River in Pike County, Pennsylvania, and 15 miles from the outcrop of this rock on Kittatinny Mountain. These Oneida boulders are found from Shohola to the mountain and on down through Pike and Monroe counties. They are most numerous near the mountain. There are two ways in which these boulders could have reached their present position: (*a*) The regional trend of the ice was more westerly than indicated by Lesley's map. In that case the ice could have carried the boulders from outcrops on Shawangunk Mountain. (*b*) There was a westerly movement of the ice which carried the boulders from Kittatinny Mountain to their present location. This latter hypothesis is supported by the westward-pointing markings on the summit of Kittatinny Mountain at High Point.

3. The striae and crescentic markings found in the Delaware gorge are oriented in direct line with the slope of the mountain, though not in a line with the glacial markings described at High Point. Glacial scorings are frequently found on the downslope, as shown east of Flatbrookville, at Mount Cube, and at many other places.

[22] *Op. cit.*, p. 43.

4. The height of the glacial mass may have been greater over Kittatinny Mountain than to the west, and, if so, there must have been a tendency for the ice to move down the sides of the mountain. If this force were sufficiently strong, its effect could have been to deflect the ice up the river gorge and away from the Neversink–lower Delaware Valley.

Though the direction of ice movement within the Delaware gorge cannot be proved from the data at hand, undoubtedly a more thorough study would soon decide the question. There is no reason to postulate more than a local movement up-valley. The ice may simply have been deflected along the sides of the gorge, shortly to resume its way to the southeast. Ice moving across Kittatinny Mountain might conceivably have exerted sufficient pressure against the "Port Jervis Gap" to force this deflection to the northwest. From the evidence of the friction cracks as determined in this study, the writer inclines to the hypothesis that the ice did move up-valley.

CONCLUSIONS

The evidence indicates that friction cracks are of definite value in determining the direction of ice movement. Striae alone are often undependable and in many places are absent. The orientation of the horns of crescentic markings is not a practical means of determination, because it varies with each of several types of glacial crescentic markings.

Field work shows that nearly all glaciated rock surfaces, in the regions studied, do contain friction cracks. Furthermore, they are still visible in many places where polishing and striae have been weathered away. In every case where friction cracks have been observed and the direction of movement is known—in the field, in the laboratory, and as described in the literature—the principal fracture has been found to dip forward in the direction of movement of the overriding agent.

ACKNOWLEDGMENTS.—Dr. Paul MacClintock, of Princeton University, has given many invaluable suggestions and criticisms during the study of the problem. Furthermore, it is largely due to his encouragement that the paper has reached its final form. Criticism by Dr. A. C. Trowbridge, of the State University of Iowa, has resulted in a total reorganization and a new approach in the presentation of material. In the field work, Mr. W. A. Bryan was of the utmost assistance because of his friendly skepticism. I am also much indebted to Mr. John Carrier, of the Iowa Geological Survey, who has spent much time and study in the preparation of the illustrations.

A METRIC GRADE SCALE FOR SEDIMENTARY ROCKS

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ABSTRACT

Studies of thin sections of sedimentary rocks, in investigations of rock facies, reveal that there is no available grade scale designed especially for two-dimensional measurements of grain size, roundness, etc. It is not possible to secure the same results from thin sections, which are random sections, as from loose grains or fragments. Igneous-rock petrographers and metallographers well recognize this fact.

In developing a new scale for this growing need, grade scales in general were studied and the principles for their construction evaluated. Upon these, with the convenience of the resulting scale constantly in mind, a metric grade scale has been devised which avoids most of the difficulties of three-dimensional scales. This scale is for thin sections of sedimentary rocks. It is not a competitor to the grade scales now in use for loose grains, such as the Wentworth scale with which sedimentary petrographers are familiar.

The relationships between measurements of three- and two-dimensional material are not here discussed. The problems are too complex for the present.

The proposed scale is given in Table 8 and in Figure 3.

INTRODUCTION

The growing importance of sedimentary-rock facies promises that more attention will be paid to studies of sedimentary rocks in thin sections. The progress in the investigation of loose grains, of recent sands, of modern lake deposits, and so on, foreshadows much work on consolidated rocks. Grain-size measurements in thin section require the development of new technique and equipment. This paper discusses the need for a new grade scale for thin sections and proposes such a scale. The areas of grains revealed by thin sections can be measured,[1] preferably in terms of nominal sectional diameters.[2] But these data are not the same as those derived from loose grains. The relationship between three-dimensional and two-dimensional measurements is not exactly known. There is, therefore, sufficient justification for proposing a scale for this specific purpose.

It was first thought that the scale of C. K. Wentworth, so well known in this country and accepted as the standard, would serve as a pattern, particularly so as the writer has used the Wentworth micrometer stage on a petrographic microscope for many years for Delesse-Rosiwal analyses. But the Wentworth scale, given in Table 1, shows many fractions, especially in decimal form, which were found inconvenient. The origin of these fractions lies in the particular constant ratio used in its construction.

In the search for the principles of

TABLE 1*

WENTWORTH GRADE SCALE

Grade Terms	Fractional (Mm.)	Decimal (Mm.)
Boulder		Above 256.000
Cobble		256.000 – 64.000
Pebble		64.000 – 4.000
Granule		4.000 – 2.000
Very coarse sand		2.000 – 1.000
Coarse sand	1 –1/2	1.000 – 0.500
Medium sand	1/2 –1/4	0.500 – 0.250
Fine sand	1/4 –1/8	0.250 – 0.125
Very fine sand	1/8 –1/16	0.125 – 0.0625
Silt	1/16–1/256	0.0625– 0.03125
Clay	Below 1/256	Below 0.03125

* Adopted from Wentworth, "A Scale of Grade and Class Terms for Clastic Sediments," *Jour. Geol.*, Vol. XXX (1922), p. 384.

[1] H. L. Alling, "A Diaphragm Method for Grain Size Analysis," *Jour. Sed. Pet.*, Vol. XI (1941), pp. 28–31.

[2] Hakon Wadell, "Volume, Shape, and Roundness of Quartz Particles," *Jour. Geol.*, Vol. XLIII (1935), p. 263.

grade scales in general, I am very grateful to W. C. Krumbein for his kindness in discussing these matters with me. His assistance is greatly appreciated.

SCALES FOR THIN SECTIONS

In designing a scale for thin sections, distinct from those for loose grains, the writer first turned to those of igneous-rock petrographers. They, too, realize that the range of grain size of earth materials is a continuous series, the division of which is purely arbitrary. To erect partitions is analogous to the subdivision of the plagioclase feldspars (see Fig. 1). All agree that the differences between two consecutive divisions of a grade scale should be greater for large sizes than for small. In other words, scales must be stretched out for small sizes and compressed for large. A suitable basis for plotting the divisional points is multiple cyclic semilogarithmic graph paper.[3]

J. P. Iddings[4] refers to "coarse," "medium," and "fine-grained" igneous rocks. He proposed that "the grain of rocks may be described more definitely by stating . . . the size of the crystals in terms of the *metric* system"[5] (see Fig. 3, col. 1). His scale is shown in Table 2. While there is a gap in this classification, it establishes the divisional points on a metric basis.

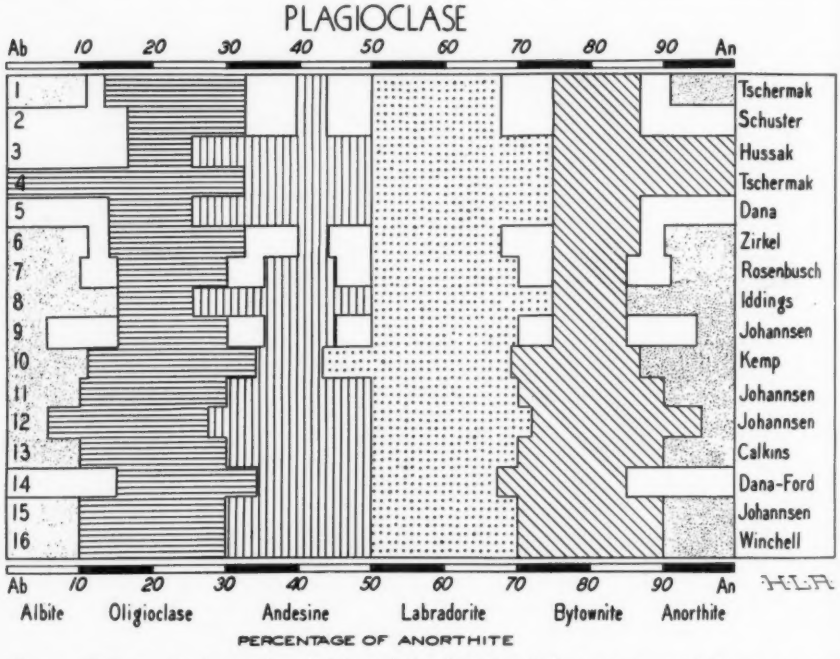

FIG. 1.—Diagram showing various divisions of the plagioclase feldspars as proposed by many petrographers. Redrawn from Albert Johannsen, *A Descriptive Petrography of the Igneous Rocks*, Vol. I (1st ed.; Chicago: University of Chicago Press, 1931), p. 29, Fig. 42.

[3] Such as Lefax semilogarithmic quadruple graph paper No. 252.

[4] *Igneous Rocks*, Vol. I (New York: John Wiley & Sons, 1909), p. 192.

[5] *Ibid.* The italics are mine.

METALLOGRAPHIC SCALES

Metallographers study their material by examining polished blocks with a reflecting microscope. They know that grain-size measurements of alloys are not the full true size.[6] They are not greatly disturbed, however, by this because the measurements of grain sizes of alloys can be secured in *no other way*. Metallographers have but one scale—a scale exactly comparable to the igneous-rock petrographer's for thin sections; and there is a need for one for sedimentary *rocks*.

Iddings' scale, on a metric basis, furnishes an excellent pattern for a scale for sedimentary rocks. It establishes the important partitions at convenient places: 0.001, 0.01, 0.1, 1, 10, 100, and 1,000 mm. These limits are here adopted.

The writer then turned to a study of grade scales set up for the classification of loose grains, fragments, sands, and soils. Eighteen different ones were collected, and these were plotted. There are others, but these are sufficient for the present purpose. The original chart was an elaborate one, not suited for reproduction in this *Journal*. However, a modified form is shown in Figure 2. The disagreements among these indicate that there is room for improvement. It reminds one of the chaotic condition of the classification of the plagioclases before F. C. Calkins'[7] sensible arrangement on a decimal basis (see Fig. 1) was proposed.

[6] Zay Jeffries, "Grain Size Measurements," *Met. and Chem. Eng.*, Vol. XVIII (1918), p. 185; Zay Jeffries and Robert S. Archer, *Science of Metals* (New York: McGraw-Hill Book Co., 1924), p. 89; Henry M. Howe, *The Metallography of Steel and Cast Iron* (New York: McGraw-Hill Book Co., 1916), p. 268.

[7] "A Decimal Grouping of the Plagioclases," *Jour. Geol.*, Vol. XXV (1917), pp. 157–59.

THE FUNCTIONS OF GRADE SCALES

A thorough discussion of the functions of grade scales is not necessary here, as the reader can be referred to W. C. Krumbein.[8] There are two distinct purposes, however, that it is well to recognize and clearly distinguish.

The first is descriptive; the second is analytic. The descriptive function is essentially to supply names, such as "sand," to definite size ranges. The analytical purpose is for statistical operations which require, for the greatest convenience, a geometrically arranged scale with a constant ratio between adjacent ranges. What has been attempted in most grade scales is to combine these two functions in one scale, which results in confusion in certain cases. The descriptive scale does not, by necessity, require a systematic constant relation between each named size range. The analytical scale should be geometric in character, as its real purpose will otherwise be defeated.

TABLE 2*

IDDINGS' SCALE FOR IGNEOUS ROCKS

	Range (Mm.)		
Meter-grained rocks.....	Above 1,000		
Decimeter-grained rocks....	100	–	1,000
Centimeter-grained rocks...	10	–	100
Millimeter-grained rocks...	1	–	10
Decimillimeter-grained rocks	0.1	–	1
Micron-grained rocks.....	0.001	–	0.01

*Iddings, *op. cit.* The arrangement is mine.

CLASS-INTERVAL SCALES

Experience has led the writer to require a third kind of scale. This is the *class-interval scale*. The purpose of these scales is to supply a suitable base for

[8] W. C. Krumbein and F. J. Pettijohn, *Manual of Sedimentary Petrography* (New York: Century Co., 1938), pp. 86–88.

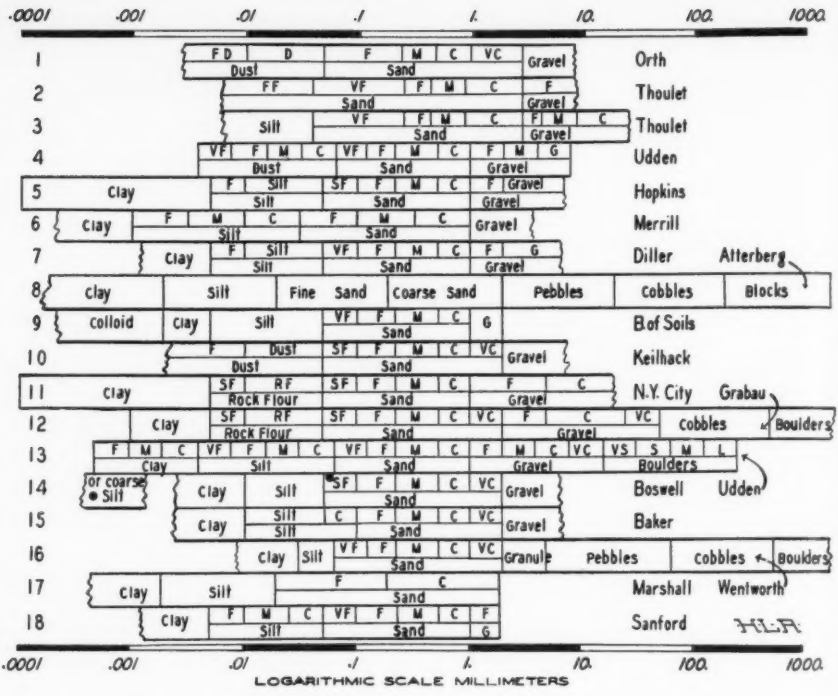

FIG. 2.—Grade scales for sediments plotted on a logarithmic scale in terms of millimeters. Legend: *C*, coarse; *D*, dust; *FF*, fine fine; *G*, gravel; *L*, large; *M*, medium; *RF*, rock flour; *S*, small; *SF*, superfine; *VF*, very fine; *VS*, very small.

1. Orth. 1875. "Bezeichnung des Sandes mach des Grösse des Kornes," *Neues Jahrb. f. Min.*, p. 551.
2. Thoulet, J. 1879 (?). *Précis d'analyse de fonds sous-marins actuel et anciens*, p. 64. Paris: R. Chapelot & Cie.
3. Thoutlet, J. 1881. "Etude mineralogique d'au Sable de Sahara," *Bull. Soc. min. France*, Vol. IV, pp. 262–68.
4. Udden, J. A. 1898. *The Mechanical Composition of Wind Deposits* ("Augustana Library Publications," No. 1), p. 6.
5. Merrill, George P. 1898. *Mechanical Analysis of Residual Sand of Diabase and of Washed Kaolin*, quoted in *U.S. Geol. Surv. Bull. 150*, p. 380.
6. Hopkins, C. G. 1899. "A Plea for a Scientific Basis for the Division of Soil Particles in Mechanical Analysis," *U.S. Dept. Agric., Dept. Chem. Bull. 56*, pp. 64–66.
7. Diller, J. S. 1902. Quoted from Grabau (see ref. 12 below).
8. Atterberg, A. 1905. "Die Klassifikation der Sande und Kiese," *Chem. Zeit.*, Vol. XXIX, pp. 195–98.
9. U.S. Bureau of Soils. 1906. *Soil Survey Field Book*, pp. 17–18.
10. Keilhack, Konrad. 1908. *Lehrbuch der praktischen Geologie*, 2te Auflage, pp. 527–28. Stuttgart: Ferdinand Enke.
11. New York City Aqueduct Comm. Probably 1913. Quoted from Grabau, *op. cit.*, p. 286.
12. Grabau, A. W. 1913. *Principles of Stratigraphy*, p. 287. New York: A. G. Seiler & Co.
13. Udden, J. A. 1914. "Mechanical Composition of Clastic Sediments," *Geol. Soc. Amer. Bull.*, Vol. XXV, pp. 655–744.
14. Boswell, P. G. H. 1918. *British Resources of Sands and Rocks Used in Glass Making*, p. 13. London: Longmans, Green & Co.
15. Baker, H. A. 1920. *On the Investigation of the Mechanical Constitution of Loose Arenaceous Sediments by the Method of Elutriation . . . . Thanet Beds . . . .*, p. 2. London: Basin, Dulan & Co.
16. Wentworth, C. K. 1922. "A Scale of Grade and Class Terms for Clastic Sediments," *Jour. Geol.*, Vol. XXX, p. 384.
17. Marshall, C. E., 1935. "Mineralogical Methods for the Study of Silts and Clays," *Zeitschr. f. Kristal.*, A, Vol. XC, p. 8.
18. Sanford, J. T. 1939. *Jour. Sed. Pet.*, Vol. IX, p. 81.

plotting data for each individual specimen. As grain sizes of sediments and rocks have a great range, it is necessary to devise scales to fit each sample. This means a set of them. The value of each class is dependent upon two requirements: first, that the total range or spread be measured and, second, that this range be divided into approximately 10 equivalent classes, each of equal value. Figure 10 is based upon a common statistical procedure; less than 10 classes may conceal important characteristics, while more than 10 may introduce artificial troughs, cusps, additional peaks, etc., in the frequency-distribution curve, which unnecessarily reduces the significance of such measurements. Standardization upon 10 leads to uniformity.

The use of such scales makes it possible to plot the data on a proper base to see the characteristics, without distortion, of the grain size of each specimen. For comparing frequency-distribution curves, however, all can be plotted to a single scale. Inasmuch as the grain-size range may be great, a logarithmic base is very satisfactory. It is well to realize that curves plotted to an arithmetic base yield a set of statistical elements which are different for the same data plotted to a logarithmic base.

The above-mentioned kinds of scales —descriptive, analytical, and class-interval—are frequently combined, as is illustrated by the customary "histogram." The point is that they do not necessarily have to be so consolidated. There are advantages in keeping them separate for specific purposes.

CHOICE OF RATIO

RATIO OF 2

The convenience of the resulting scale will depend upon the ratio employed. J. A. Udden[9] in 1898 was apparently the first to propose the factor 2. Wentworth[10] in 1922 adopted the same figure. This particular number, however, leads to inconvenient fractions, which was the initial objection. Wentworth's reason for the adoption of 2 is that it is "the most convenient ratio for the construction of such a series. . . . ." If convenience is one of the criteria for a satisfactory scale, as here assumed and as Wentworth seems to imply, one may ask: Just why is 2 the most convenient ratio when 10 leads to a more convenient scale?

Wentworth further suggests that, if additional subdivisions are needed, the ratio $\sqrt[3]{2}$ could be used, "or in exceptional cases, $\sqrt[4]{2}$."

RATIO OF 10

A. Atterberg[11] recognized that there were other ratios that lead to more convenient scales and proposed the value of 10. But, instead of "starting" at 1, he began at 2. Consequently, his divisional points are as follows: 0.002, 0.02, 0.2, 2, 20, and 200. This scale has vogue in Europe. This ratio is metric in principle and furnishes the basis for a satisfactory scale. It is here accepted as one of the bases for a scale for thin sections.

HOPKINS' RATIOS

C. G. Hopkins[12] in 1899 proposed a ratio of the square root of 10 for a greater subdivision of sizes than the simple ratio of 10 provides. In addition, Hopkins suggested the ratio of the fourth root of 10 for more subdivisions. Hopkins' sugges-

[9] "The Mechanical Composition of Wind Deposits," *Augustana Library Pub. 1* (1898).

[10] *Op. cit.*, p. 382.

[11] "Die Klassifikation der Sande und Kiese," *Chem. Zeitung*, Vol. XXIX (1905), pp. 195–98.

[12] "A Plea for a Scientific Basis for a Division of Soil Particles in Mechanical Analysis," *U.S. Dept. Agric., Dept. Chem. Bull. 56* (1899), pp. 64–66.

tions will receive more attention below. These ratios are accepted as sound and are used in the proposed scale.

MAJOR AND MINOR GRADE TERMS

Wentworth[13] lists the following grade scales: "boulder," "cobble," "granule," "sand," "silt," and "clay." He further divides "sand" into five smaller units, "very coarse," "coarse," "medium," "fine," and "very fine sand," but does not subdivide any of the other grade terms. He proceeds to put the small units alongside the large units and then applies his geometrical scale with the constant ratio of 2 to all of them. This ignores the difference in magnitude of the terms; "coarse sand" is a term of lower magnitude than "gravel."

MAJOR PARTITIONS

Recognition of the two kinds of terms, major and minor, appears to be one of the necessities of any grade scale. The ratio of 10 used by Atterberg makes the spaces devoted to "clay," "silt," "pebbles," "cobbles," and "blocks" all the same in width on a logarithmic base. His only departure from this simple plan is the treatment of "sand," distinguishing "coarse" and "fine" sand and giving to each the same space as to the major units. But Atterberg's starting-point of 2, as already noted, is different from the majority of scales. If, however, 1 be taken as the place of departure as in most scales, and the ratio of 10 be retained, the major units are delimited by simple, easily remembered divisional partitions: 0.001, 0.01, 0.1, 1, 10, 100, and 1,000.

Let us see if the above procedure fits the scales that have been devised. At first glance it appears that it does not. A closer examination, however, of the 18 scales shown in Figure 2 reveals that "sand" is divided into a number of minor units.[14] Six scales use "very coarse sand," the lower limit of which in all cases is 1 mm. If "very coarse sand" is eliminated as being equivalent to "very fine gravel" or "fine gravel," then 14 of the 18 scales have the upper limit of "sand" at this point. The same kind of reasoning can be applied to the lower limit of "sand" as well. If "very fine sand" is regarded as the same as "very coarse silt," then 9 of the 18 scales coincide at 0.1 mm. Thus, with this method, the majority of the scales do fit the proposal. The application of this principle to the Wentworth scale shows only partial agreement, however. The upper limit is the same if "very coarse sand" is eliminated. The lower limit, however, does not fit. Wentworth places it at 0.0625 mm. instead of 0.1 mm., as advocated in this paper.

The establishment of the major terms at these convenient "whole" numbers does no great violence to most of the scales, if the above reasoning is used. Consequently, it is here adopted.

NAMING THE MAJOR DIVISIONS

An examination of the 18 scales shows that there are 12 available major names. "Sand" is used by all, "gravel" by most, "silt" and "clay" by 13; the other terms are used to much less extent. "Cobbles" and "boulders" are used by 3; "dust" appears 3 times; "rock flour" (which apparently is another way of expressing "silt") occurs twice. "Colloid," "blocks," and "granule" are each shown once.

One of the striking observations to be made about these scales, as plotted in Figure 2, is that many fail to span the complete range of size; most of them are

[13] *Op. cit.*, pp. 379–81.

[14] Of the 18 scales: 2 twofold, 1 threefold, 11 fourfold, 4 fivefold.

confined to a few major divisions centering about "sand." This limits the number of available opinions regarding suitable names to be applied to the extreme grades.

Of the 12 names for major grades supplied by these scales, the writer has found 7 that will serve satisfactorily.

AGGREGATE TERMS

The choice of names assigned to major grade units should be applicable as aggregates. "Sand" is perfectly satisfactory because it becomes "sandstone" with the addition of the suffix "stone." "Claystone," "siltstone," "gravelstone," and "cobblestone" are acceptable with varying degrees of success. "Colloidstone" and "boulderstone" may appear strange and less acceptable; but the writer, having used them, does not find them so.

It has been difficult to use two of Wentworth's[15] terms—"granule" and "pebble." These have been omitted from the proposed scale. "Granule" does not appear on any other scale. The inclusion of "granule" and "pebble" in Wentworth's scale gives "cobble" a higher size value than is shown on other scales. "Granule" does not form a satisfactory aggregate term; "granulestone" seems out of step with the others.

The above discussion leads to the conclusion that the following seven terms for the major terms will serve: "colloid," "clay," "slit," "sand," "gravel," "cobbles," and "boulders." These "correlate" well with Iddings' scale for igneous rocks, as shown in Table 3.

THE MINOR UNITS

The subdivision of the major units—"gravel," "sand," "silt," and so on—is another problem of a satisfactory scale. There are at least two approaches: one is arithmetical and the other is logarithmic. Most of these scales in Figure 3 are essentially arithmetical.

TABLE 3

TABULATION OF MAJOR DIVISIONS: IGNEOUS AND SEDIMENTARY ROCKS

Sizes in Millimeters	Igneous Rocks (Iddings)	Sedimentary Rocks (Alling)
100 – 1,000	Decimeter-grained rocks	Boulders
10 – 100	Centimeter-grained rocks	Cobbles
1 – 10	Millimeter-grained rocks	Gravel
0.1 – 1	Decimillimeter-grained rocks	Sand
0.01 – 0.1	Centimillimeter-grained rocks*	Silt
0.001 – 0.01	Micron-grained rocks	Clay
0.0001 – 0.001	Gap	Colloid

* Added by author.

ARITHMETICAL SCALES

The major units are usually divided on a three-, four-, or fivefold basis by simple arithmetical fractions (or decimals). Table 4 shows two such schemes.

TABLE 4

ATTEMPTS TO DIVIDE MAJOR UNITS

Threefold		Fivefold	
Range (Mm.)	Name	Range (Mm.)	Name
		0.1–0.2	Very fine sand
0.1 –0.25	Fine sand	0.2–0.4	Fine sand
		0.4–0.6	Medium sand
0.25–0.5	Medium sand	0.6–0.8	Coarse sand
0.5 –1.0	Coarse sand	0.8–1.0	Very coarse sand
Approximately equal widths on logarithmic scale		Unequal widths on logarithmic scale	

The advantage of the threefold scheme in Table 4 is the approximate equal spacing on a logarithmic scale. I have found this scale fairly satisfactory. The disadvantages arise when this grade scale is used for statistical analysis, as Krumbein[16] has kindly pointed out to me. His objection is expressed in Table 5.

[15] *Op. cit.*, p. 380.

[16] Personal communication, March, 1942.

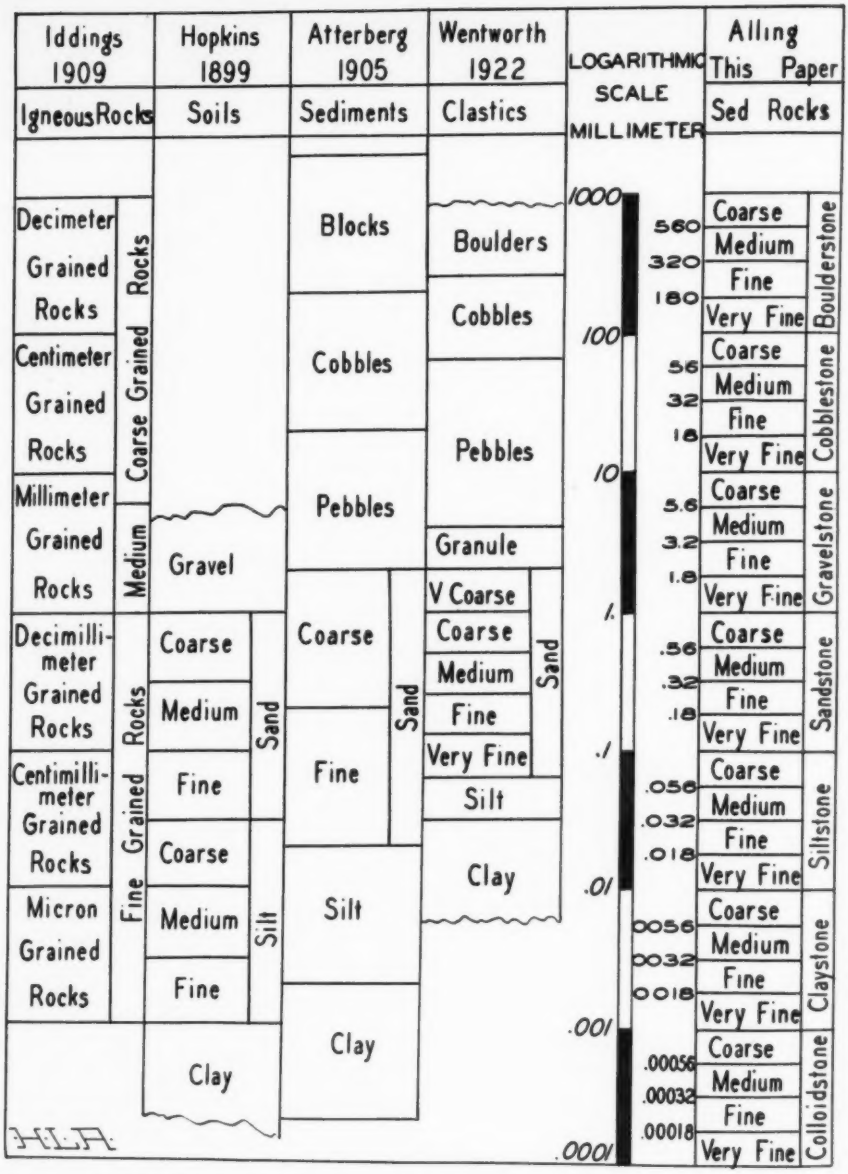

FIG. 3.—Plot of five scales for various purposes including the proposed scale for sedimentary rocks. Logarithmic scale, in millimeters.

Iddings, J. P. 1909. *Igneous Rocks*, Vol. I, p. 192. New York: John Wiley & Sons.
Hopkins, C. G. 1899. *U.S. Dept. Agric., Dept. Chem. Bull. 56*, pp. 64–66.
Grabau, A. W. 1913. *Principles of Stratigraphy*, p. 287. New York: A. G. Seiler & Co.
Wentworth, C. K. 1922. *Jour. Geol.*, Vol. XXX, p. 384.
Alling, Harold L. 1942. This paper.

Of course, these objections are very pertinent. After trying many arithmetical divisions, the present writer is convinced that only a logarithmic scale will avoid the difficulties.

LOGARITHMIC SCALES

Hopkins'[17] paper reveals that he had the same difficulty long ago. Investigators have not been properly impressed by his point of view. Hopkins was critical,

TABLE 5

INCONSISTENCIES OF ARITHMETICAL DIVISION

Threefold Divisions	Ratio*	Logarithmic Units	Difference†
0.1 –0.25	10/5 =2	log 10 =1.00	0.3
0.25–0.50	5/2.5=2	log 5 =0.70	0.3
0.50–1.0	2.5/1=2.5	log 2.5=0.40	0.4
		log 1 =0.00	

* Not a constant geometric ratio.

† Logarithmic units not suitable for statistical analysis.

as is the writer, of the position of the limiting partitions of the usual scales. He says:

> These limits were originally chosen by mere chance and have no more of a scientific basis than have common systems of weights and measures or the Fahrenheit thermometer scale. . . . . One serious objection to this system is that the ratio of the diameter of the largest particles to that of the smallest particles in each of the various divisions is not a constant. . . . . Because of this objection . . . . [Hopkins proposed in 1897] the system illustrated in the following table [Table 6]. It was subsequently adopted by the department of soil physics of the University of Illinois, and has since been employed with entire satisfaction.

It is well to note that Hopkins wrote this in 1899. It needs stressing today. The basis of this scale is the ratio constant of $\sqrt[3]{10}$, which equals 3.16227, or approximately 3.2. This results in a bisection of the major terms into two equal parts, as plotted on a logarithmic base. As two minor terms may not be sufficient for a satisfactory scale, Hopkins suggests that further division could be made by using the fourth root of 10, which equals 1.77828, or 1.8 approximately.

The divisional points can be expressed in a different form:

The antilogarithm of 0.7500000 = 5.62341, or approximately 5.6
The antilogarithm of 0.5000000 = 3.16227, or approximately 3.2
The antilogarithm of 0.2500000 = 1.77828, or approximately 1.8

This results in equal quartering—a fourfold division. Hopkins' ratios are so satisfactory that they are adopted for the proposed scale.

TABLE 6

GRADE SCALE OF HOPKINS,* 1899

	Millimeters
Gravel	Greater than 1
Coarse sand	1 –0.32
Medium sand	0.32 –0.1
Fine sand	0.1 –0.032
Coarse silt	0.032 –0.01
Medium silt	0.01 –0.0032
Fine silt	0.0032–0.001
Clay	Less than 0.001

* *Op. cit.*

NAMING THE MINOR UNITS

Having decided upon four minor units for each of the seven major divisions, the naming of these remains to be done. An examination of the 18 scales (Fig. 2) reveals that there are seven terms used for subdividing "sand." In Table 7 the frequency of use is shown. The writer has adopted the four terms most used: "very fine," "fine," "medium," and "coarse."

THE PROPOSED SCALE FOR SEDIMENTARY ROCKS

The search for a satisfactory grade scale for thin-section measurements has resulted in the conclusion that a new one is justified. The unfortunate choice of a

[17] *Op. cit.*, pp. 64–66.

constant ratio of 2, as is illustrated by the scales of Udden and Wentworth, results in inconveniences which are avoided by a ratio of 10, as used by Atterberg and Hopkins. The ratio of 10 is here adopted. The distinction and establishment of the major grade terms on a decimal basis, with partitions at 0.0001, 0.001, 0.01, 0.1, 1, 10, 100, and 1,000 mm. has much to commend it and is a part of the proposed scale. These divisional points furnish seven spaces for "colloid," "clay," "silt," "sand," "gravel," "cobbles," and "boulders," all of which are suitable names, as they lend themselves to aggregate terms such as "siltstone," "sandstone," "gravelstone," etc. The division of the minor grade terms can well be accomplished by the use of the ratio $\sqrt[4]{10}$, as proposed by Hopkins. This provides a fourfold equal spacing, as plotted upon a logarithmic base, for the minor terms "very fine," "fine," "medium," and "coarse." This scale is given in Table 8.

TABLE 7

FREQUENCY OF USE OF SUBDIVISIONS OF SAND

Name	No.
Fine fine sand	1
Superfine sand	5
Very fine sand	8
Fine sand	18
Medium sand	16
Coarse sand	18
Very coarse sand	6

CONCLUSIONS

Facies studies of sedimentary rocks in the form of thin sections require the use of a grade scale designed for this express purpose. As such a scale does not exist, the writer has investigated scales proposed for three-dimensional measurements of loose grains and fragments, in order to discover the principles upon which a satisfactory scale can be built. It is believed that the following are fundamental to that end:

1. Grain sizes constitute a continuous series.

2. Any division of this series is an arbitrary matter.

3. Convenience in use of any grade scale is a required criterion.

4. Statistical analysis requires that a constant geometrical ratio be used.

5. There are two kinds of divisions: major and minor. "Silt," "sand," and "gravel" are major terms; "very fine sand," "fine sand," "medium sand," and "coarse sand" are minor terms.

6. The major terms are most satisfactorily delimited by the use of the constant ratio of 10. This establishes the major units at the very convenient points: 0.0001, 0.001, 0.01, 0.1, 1, 10, 100, and 1,000 mm. These partition positions do no great violence to existing scales. Extension, if needed, in either direction is, of course, entirely possible.

7. The use of the ratio of the fourth root of 10, as proposed by Hopkins, divides the major units fourfold. These are equal in width when plotted on a logarithmic base. The partitions are placed at 0.1, 0.18, 0.32, 0.56, and 1.0, or times 10, 100, etc., or times 1/10, 1/100, etc., depending upon direction.

8. The names of the minor units are readily forthcoming, as they are in common use, especially for "sand." The extension of this simple plan to "silt," "gravel," etc., is a logical one. This furnishes the following terms: "very fine," "fine," "medium," and "coarse."

9. The use of the above principles results in the proposed metric grade scale, given in Table 8 and Figure 3.

10. This proposed scale is not for

three-dimensional measurements, for which the Wentworth scale was especially designed.

11. The proposed scale is for use for thin sections and polished blocks.

12. No competition between the two scales is in any way expressed or implied. Each scale fills a need for a different purpose.

13. The relationship between the three-dimensional and the two-dimensional scales is not discussed in this paper. The problems are much too complex for consideration at this time.

TABLE 8

PROPOSED METRIC GRADE SCALE, ALLING, 1942

Major Divisions	Minor Divisions	Size Range (Mm.)	Aggregate Term
Boulder	Coarse	560 – 1,000	Boulderstone
	Medium	320 – 560	
	Fine	180 – 320	
	Very fine	100 – 180	
Cobbles	Coarse	56 – 100	Cobblestone
	Medium	32 – 56	
	Fine	18 – 32	
	Very fine	10 – 18	
Gravel	Coarse	5.6 – 10.0	Gravelstone
	Medium	3.2 – 5.6	
	Fine	1.8 – 3.2	
	Very fine	1.0 – 1.8	
Sand	Coarse	0.56 – 1.0	Sandstone
	Medium	0.32 – 0.56	
	Fine	0.18 – 0.32	
	Very fine	0.10 – 0.18	
Silt	Coarse	0.056 – 0.10	Siltstone
	Medium	0.032 – 0.056	
	Fine	0.018 – 0.032	
	Very fine	0.010 – 0.018	
Clay	Coarse	0.0056 – 0.01	Claystone
	Medium	0.0032 – 0.0056	
	Fine	0.0018 – 0.0032	
	Very fine	0.001 – 0.0018	
Colloid	Coarse	0.00056 – 0.001	Colloidstone
	Medium	0.00032 – 0.00056	
	Fine	0.00018 – 0.00032	
	Very fine	0.0001 – 0.00018	

GLACIAL POTHOLES ON OUTPOST ISLANDS, GREAT SLAVE LAKE, NORTHWEST TERRITORIES

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ABSTRACT

A group of glacial potholes on Outpost Islands, Great Slave Lake, is described, and their bearing on the origin of glacial potholes discussed. It is concluded that such potholes are formed by *moulins* from which the water impinges on the bedrock at an angle and also by subglacial streams flowing away from such *moulins*.

INTRODUCTION

During the summer of 1937, while engaged in the development of gold claims on the Outpost Islands in Great Slave Lake, Northwest Territories, the writer found and mapped a group of potholes. One of these ranks among the largest so far described. Because of this and other characteristics, their occurrence seems to merit recording.

The Outpost Islands form an archipelago 25 miles due north of the eastern side of the Slave River Delta. The holes are on one of the western islands of the group, on mineral claim Fox 18 which is part of the property of the Great Slave Lake Gold Mines Company.

The topography is typically pre-Cambrian with low relief. Glacial planing has been strong in the Great Slave Lake area and shows well in the Outpost Islands, where all formations, except the quartzites, have been planed into whaleback shapes and glacial pavements. The average elevation of the islands is 40–50 feet above lake level, with some areas of quartzite reaching heights of 200 feet. There is very little drift, about one-half the land surface being bare rock.

DESCRIPTION OF POTHOLES

The potholes are cut into hard arkose. They are sharply incised from the surface and, with one or two exceptions, have vertical walls. The largest hole is on the highest point of land in the vicinity, some 40 feet above the lake. From this place the rock slopes rather sharply to the lake to the northwest and southeast and gradually to the southwest. The ridge on which the hole occurs continues toward the northeast at about the same elevation. There is no land form of any kind to provide a waterfall to incise the large hole. Some of the other holes are on the rock slope to the northwest already mentioned.

The horizontal dimensions of the large hole are 28 × 25 feet. Vertically, it is 15 feet to the top of the debris, on which stood 4 feet of water. This seems to be near the maximum size attained by potholes. One with a diameter of 30 feet is described by P. McKellar.[1] One in Pennsylvania[2] is 42 × 24 feet, but this may be a compound pothole above, merging into a single hole with depth. The largest in the Interstate Park near Taylor's Falls, Minnesota, is 27 × 25 feet.

The depth of only one of the Outpost holes was ascertained. This hole had a diameter of 4 feet, was 5 feet down to the

[1] "On Potholes North of Lake Superior Unconnected with Existing Streams," *Bull. Geol. Soc. Amer.*, Vol. I (1890), pp. 568–69.

[2] C. C. Ashburner, *Geol. Surv. of Pa. Ann. Rept.* (1865), pp. 615–25.

FIG. 1.—View of Outpost Islands at the headframe of the shaft of Great Slave Lake Gold Mines

FIG. 2.—View of large pothole

top of the debris, and contained 5 feet of debris, mostly cobbles, sand, and gravel. The Interstate Park holes are the deepest known. One of these, with a diameter of 10–12 feet, has been excavated to a depth of 84 feet without reaching bedrock. These holes, however, are stream waterfall potholes, as they are located in the postglacial gorge of the St. Croix River.[3] This fact was further substantiated in 1905, when, during the damming of the river for a power plant, potholes were seen exposed close to where the foot of the falls had been in 1904.[4] Such great depths may not be attained by glacial potholes, owing to a lesser degree of permanence than have river falls over resistant rock.

The material taken from the Outpost pothole was roughly sorted into an upper 3 feet of cobbles, gravel, and sand and a lower 2 feet of gravel and sand with only sand next to rock bottom. The cobbles were of a variety of rock types and in varying stages of roundness, which in part were based on the structural nature of the rock. A number of cobbles of almost perfect roundness were found. Of these, the gabbroic type predominated, no doubt owing to the homogeneity and toughness of this rock. Maximum diameters were about 4 inches. Bedrock at the bottom of the hole was smooth. The removal of material from this hole had an economic, rather than a scientific, motive, as there were high-grade gold veins about ½ mile distant, and it was hoped that some nuggets might be trapped. Careful panning showed no colors. Thus, instead of a scientific pursuit yielding an economic result, in this case the tables were turned.

[3] R. T. Chamberlin, "The Glacial Features of the St. Croix Dalles Region," *Jour. Geol.*, Vol. XIII (1905), pp. 254–55, and personal communication.

[4] Chamberlin, personal communication.

Partial holes also occur in this locality. Just northwest of the large hole is a serrated scarp from 10 to 15 feet high which is formed by a series of partial holes, as shown on the plan (Fig. 3). They appear to have been a series of linked or joined holes with diameters up to 20 feet from which one side has completely disappeared. Drift at the foot of the scarp obscures the deeper parts of these holes.

The linked holes are an interesting feature of this pothole occurrence. In most cases the linking appears to be due to a recession of the cutting agent northeastward up the slope. Following, or perhaps even during, the formation of each hole, another seems to have been started above it; and this eventually joined it. In one case the partition between two holes has been cut through some 8 feet below the surface, so that, by stooping, it is possible to walk from one hole into the other. A spruce tree some 10 inches in diameter is growing in one of these holes.

A significant fact about the Outpost Island holes is that they are cut into striated surfaces. This is further emphasized by grooves an inch or more deep, worn into the striated rock surface by the overflow from some of the holes. These waterworn surfaces themselves show no striation. Thus there was no glacial erosion following the formation of the potholes, dating them with the last glacier recession. This overflow erosion is distinct enough to show the direction of water flow, as indicated by the arrows on the plan. This is about normal to the direction of glacier movement, which here was from a direction N. 60° E.

In addition to the grouped potholes just described, small, isolated holes about 6 inches in diameter were seen in the areas of quartzite a mile away. There was no stream action associated with these outside the holes themselves.

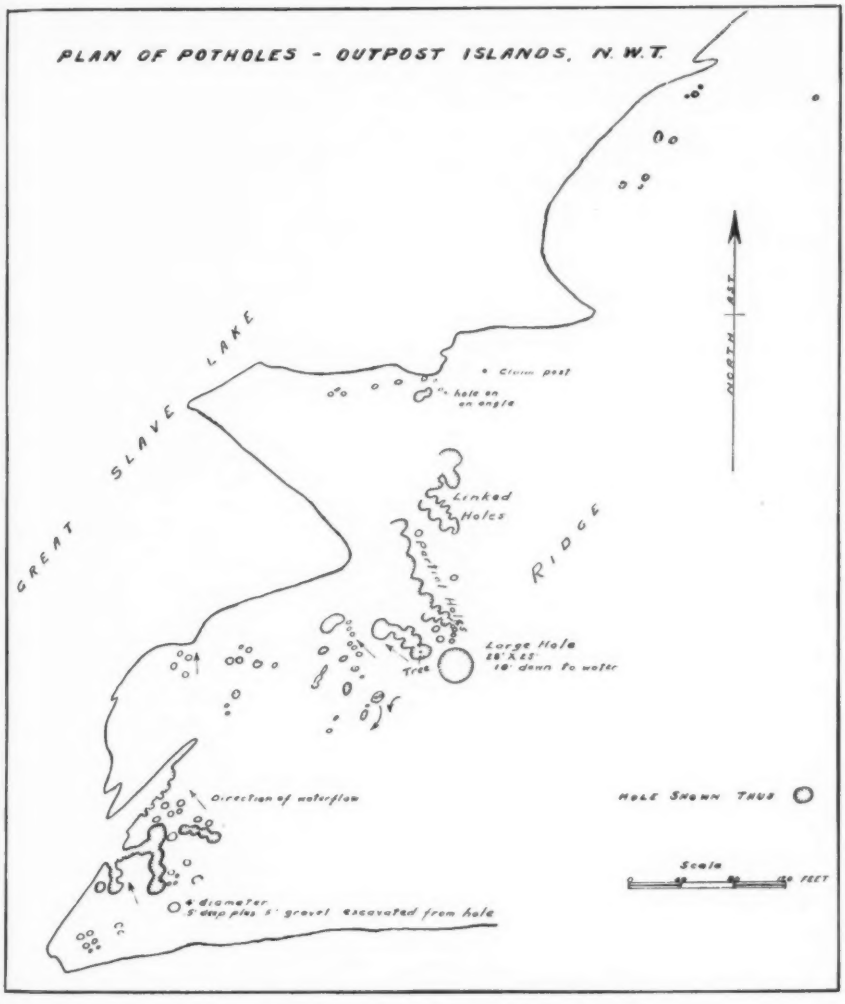

FIG. 3.—Plan of potholes, Outpost Islands, Northwest Territories

BEARING ON POTHOLE ORIGIN

Pothole literature is relatively scarce. A fairly complete set of references may be found in papers by Warren Upham[5] and H. S. Alexander.[6] Additional significant references are papers by J. E. Marr[7] and W. Stanley.[8] Upham's paper summarized opinions and evidence. His general conclusion was that glacial potholes were largely the work of glacial mills, or *moulins*.

> For the largest and deepest of the giant's kettles . . . . I cannot doubt that the pothole was cut down exactly at the foot of a great and very deep moulin by its powerful descending current.[9]

This hypothesis was challenged by Alexander, who attempted to reproduce these conditions artificially. As glacial potholes are the result of an eddying action, he produced an eddying by means of a directed water jet; but at no time was he able to cause an eddying motion by vertical or near-vertical streams. The maximum effect was secured through a jet set at an angle of 60° from the horizontal. The writer has also tried by various means to produce a circular motion in a column of water by a vertically falling current. This can be done only where the vertically falling water is deflected by striking a sloping surface. However, these experiments only demonstrate that eddy holes cannot be formed exactly at the foot of a vertical *moulin*.

Alexander further says:

> The main objection to the hypothesis lies in the difficulty of conceiving the moulin as existing long enough in the necessary definite form at the same spot or as reforming in the same manner and in the same spot often enough to account for the work accomplished.[10]

This leads him to the conclusion that glacial potholes are formed only by subglacial streams which appear near the margin of the retreating ice.

There is no doubt that some potholes are formed in this manner. A number of the Outpost holes occurring on the northwestern slope to the lake were formed by subglacial streams, as is clearly shown by the grooves incised in the bedrock by the overflow from holes higher up. It is not true, however, for the large hole which occurs on the crest of the ridge with no higher topographic form to give it a fall and with no evidence of stream action leading to the hole. A reasonable assumption is that the water here poured through the ice at a steep angle in considerable volume.

It is a matter of record that glacial potholes commonly appear where there are surface irregularities in the bedrock and consequently where crevasses are likely to occur in overriding ice. Such crevasses should persist as long as there are no great changes in the shape either of the underlying bedrock or of the ice above by excessive melting. The former is unlikely to take place where the rock is resistant and the glacial movement slow. The ice sheet might well remain thick for many years, particularly in the latitude of Great Slave Lake; and under some conditions water courses might continue the same summer after summer.

The length of time it takes a pothole to form must depend largely upon the hardness of the rock and the whirling speed of the water. Upham suggests that

[5] "Giant's Kettles Eroded by Moulin Torrents," *Bull. Geol, Soc. Amer.*, Vol. XII (1901), pp. 25–44.

[6] "Pothole Erosion," *Jour. Geol.*, Vol. XL (1932), pp. 305–37.

[7] "The Kailpot, Ullswater," *Geol. Mag.*, Vol. LXII (1926), p. 338.

[8] "Pleistocene Potholes in Clarke Mountains, Ontario," *Mich. Acad. Sci. Papers*, Vol. XIX (1934), pp. 401–12.

[9] *Op. cit.*, p. 29.

[10] *Op. cit.*, p. 314.

a single season might be long enough in some cases. Many glacial potholes are found in resistant pre-Cambrian rock, and it seems more likely that a *moulin* would remain in the same place for a number of years than that an eddy hole could be cut in one season.

A slowly retreating *moulin* might explain the linked holes at Outpost Islands. A hypothesis for the partial holes is more difficult to find. Upham suggests that one-half the hole was ice. This is hardly possible, owing to the great difference in the hardness of ice and rock. In the case of the single holes, they might have been started close to the edge of a slope and cut out to it. The escaping water could have worn down the thin edges remaining, and eventually a half or three-quarter round hole appeared. In the case of the serrated scarp formed of partial round holes, a series of linked holes may have been started near the edge of an earlier scarp and, retreating parallel to it, cut off a slab, which, falling away, left a new serrated scarp. The linked holes just northeast of the scarp show this possibility, as may be seen from the plan.

SUMMARY

The potholes described at Outpost Islands appear to have developed during the last glacial retreat from that area. The location of the largest one and some of the others suggests that the water which formed them flowed downward from the surface of the ice. Others were formed by the runoff from these holes. Vertically falling water cannot produce the eddying currents necessary to cut potholes, but water emerging from the ice at an inclined angle can do so. The *moulin* hypothesis, modified to give the water an angle from the vertical at its point of emergence from the ice, will explain the holes on topographic highs on the Outpost Islands and other places. It is considered that crevasses caused by the configuration of the underlying bedrock would remain in the same positions for a sufficient number of years to permit the cutting of the holes.

STUDIES FOR STUDENTS

THE ASSOCIATION OF COLLEGE GEOLOGY TEACHERS: REFERENCE LIST IN EARTH SCIENCES[1]

Compiled by

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FOREWORD

A teacher, ordinarily well acquainted with textbooks in his special field, is commonly not so familiar with the best works of a popular and semipopular nature. This bibliography is intended as a medium through which he may encourage the interest and guide the reading both of his students and of the laymen who occasionally seek references.[2] It should prove especially helpful to those nonprofessional students and alumni who wish to pursue geology beyond the course or two of their college programs.

Preparation of the list was inspired by the major objectives of the Association

. . . . to foster unity and cooperation among college teachers of the earth sciences, ... to promote high standards of college instruction, ... to emphasize the cultural significance of the earth sciences, and to disseminate accurate geological knowledge to the public.

The list is admittedly incomplete. It includes only those books (and a few special articles) that have come to the compiler's attention and have been recommended by competent geologists during the last three years. Omission of a book is not an adverse criticism of it; and inclusion on the list is not a guaranty of perfection. The order of listing is of no significance. Some textbooks are included to provide interested laymen with references to standard works.

MAJOR SUBDIVISIONS

General Geology
  Special Topics
    Geomorphology (Landscapes and Scenery)
    Earthquakes and Volcanoes
    Glaciation
    Deserts
    Weather (Meteorology)
    Miscellaneous
Historical Geology and Paleontology
    Plant Evolution (Paleobotany)
    Animal Evolution
    Human Evolution (Anthropology)
Economic Geology and Geography
    Conservation
    Minerals and Gemstones
    Coal, Petroleum, and Natural Gas
    Metals
History of Geology
Geography and Exploration
Military Geology
Earth's Place in the Universe (Astronomy)

[1] This list is a combination of three separate lists issued by the Association in mimeographed form each year since 1940. An increasing demand from all over the country has demonstrated their usefulness. The editors of the *Journal of Geology* are glad to encourage this contribution to improved teaching and popularization of earth sciences by providing wider circulation of the combined list.

[2] The *Scientific Book Club Review* has been invaluable in gathering this material. Readers are referred to it for editorial comment on many of the works listed. The writer is also indebted to the many colleagues who helped to prepare the list, and he will welcome corrections, additions, or suggestions for further improving this service to geology teachers and laymen.

GENERAL GEOLOGY[3]

A. VICTOR T. ALLEN. *This Earth of Ours.* Bruce Publishers, 1939. $3.50. Ryerson Press, 1939. $2.50.

A. CARROLL LANE FENTON. *Our Amazing Earth.* Doubleday, Doran, 1938. $4.50.

A. ALLAN L. BENSON. *The Story of Geology.* New York: Cosmopolitan Book Corp., 1931. $5.00.

A. K. F. MATHER. *Old Mother Earth.* Harvard University Press, 1928. $2.50.

A. WILLIS T. LEE. *Stories in Stone.* Chautauqua Press, 1927. $6.00.

A. CARROLL LANE FENTON and MILDRED ADAMS FENTON. *The Rock Book.* Doubleday, Doran, 1940. $6.00.

B. C. G. CRONEIS and W. C. KRUMBEIN. *Down to Earth.* University of Chicago Press, 1936. $3.75.

B. S. J. SHAND. *Earth Lore.* E. P. Dutton & Co., 1938. $1.75.

B. W. H. HOBBS. *Earth Features and Their Meaning.* 2d ed. Macmillan, 1931. $4.50.

B. CHARLES SCHUCHERT and CLARA M. LEVENE. *The Earth and Its Rhythms.* Appleton, 1927. $4.00.

B. J HARLEN BRETZ. *Earth Sciences.* Wiley, 1940. $1.50.

J. KARL MOSELEY. *The Earth for Sam.* Harcourt, Brace, 1930. $3.50.

J. RAMON COFFMAN. *The Child's Story of Science.* G. P. Putnam Sons, 1939. $2.50.

C. W. M. AGAR, R. F. FLINT, and C. R. LONGWELL. *Geology from Original Sources.* Holt, 1929. $3.75.

C. M. P. BILLINGS. *Structural Geology.* Prentice-Hall, 1942. $4.50.

C. F. H. LAHEE. *Field Geology.* 4th ed. McGraw-Hill, 1941. $5.00.

B. N. E. A. HINDS. *Geomorphology.* Prentice-Hall, 1942. $5.00.

C. C. A. COTTON. *Geomorphology.* 3d ed. Whitcombe & Tombs, Ltd., 1942.

C. A. K. LOBECK. *Geomorphology.* McGraw-Hill, 1939. $5.00.

C. O. D. VON ENGELN. *Geomorphology.* Macmillan, 1942. $4.50.

[3] The key letters indicate: A, written primarily for the layman in lucid, entertaining style—popularized science; B, more technical works designed for the layman and for the beginning student; C, textbooks and important technical articles; and J, written primarily for children—juvenile books.

C. EDWARD GREENLY and HOWEL WILLIAMS. *Methods in Geological Surveying.* London: Thos. Murby & Co., 1930. $7.00.

SPECIAL TOPICS

LANDSCAPES AND SCENERY

A. A. K. LOBECK. *Airways of America (Guidebook No. 1).* Geographical Press, Columbia University, 1933. $2.50.

B. W. W. ATWOOD. *Physiographic Provinces of North America.* Ginn, 1940. $4.80.

B. RODERICK PEATTIE. *Mountain Geography.* Harvard University Press, 1936. $4.00.

A. C. A. COTTON. *Landscape.* Macmillan, 1942. $6.00.

C. F. B. LOOMIS. *Physiography of the United States.* Doubleday, Doran, 1938. $2.75.

B. N. E. A. HINDS. *Geomorphology.* Prentice-Hall, 1942. $5.00.

C. A. K. LOBECK. *Geomorphology.* McGraw-Hill, 1939. $5.00.

C. O. D. VON ENGELN. *Geomorphology.* Macmillan, 1942. $4.50.

A. DANIEL E. WILLARD. *Adventures in Scenery: A Popular Reader of California Geology.* Lancaster, Pa.: Jacques Cattell Press, 1942. $3.75.

C. D. W. JOHNSON. *New England Acadian Shoreline.* Wiley, 1925. $8.50.

A. F. M. FRYXELL. *The Tetons: Interpretations of a Mountain Landscape.* University of California Press, 1938. $1.50.

B. O. W. FREEMAN and H. W. MARTIN. *The Pacific Northwest.* Wiley, 1942. $4.00.

A. R. L. G. IRVING. *Ten Great Mountains.* E. P. Dutton & Co., 1940. $3.75.

A. W. D. SMITH. *The Scenic Treasure-House of Oregon.* Portland: Binford & Mort, 1941. $2.00.

A. HOWEL WILLIAMS. *Crater Lake: The Story of Its Origin.* University of California Press, 1941. $1.75.

A. C. M. BAUER. *The Story of Yellowstone Geysers.* Haynes Inc., Yellowstone Park, Wyo., 1937. $1.50.

B. C. A. COTTON. *Climatic Accidents in Landscape Making.* Macmillan, 1942. $4.75.

B. GLENN C. FORRESTER. "The Story the Rocks Tell about Niagara Falls," *Amer. Chem. Soc.* (News ed.), Vol. XX (1942), pp. 899–902.

C. J. J. VAN NOUHUYS. "Geologic Interpretation of Aerial Photographs," *Amer. Inst. Mining Engineers Tech. Pub. 825* (1937);

Amer. Inst. Mining Engineers Transactions, Vol. CXXVI (1937), pp. 507–624.

C. W. F. HEAVEY. *Map and Aerial Photo Reading Simplified*. Harrisburg: Military Service Publishing Co., 1940. $1.00.

C. H. T. U. SMITH. "Aerial Photographs in Geomorphic Studies," *Jour. Geomorph.*, Vol. IV (1941), pp. 171–205.

C. J. L. RICH. "A Bird's-Eye Cross Section of the Central Appalachian Mountains and Plateau: Washington to Cincinnati," *Geog. Review*, Vol. XXIX (1939), pp. 561–86.

EARTHQUAKES AND VOLCANOES

B. JOSEPH LYNCH. *Our Trembling Earth*. Dodd, 1940. $3.00.

B. C. DAVISON. *Great Earthquakes*. London: Thos. Murby & Co., 1936. 17*s*. 6*d*.

C. N. H. HECK. *Earthquakes*. Princeton University Press, 1936. $3.50.

A. HOWEL WILLIAMS. *Crater Lake: The Story of Its Origin*. University of California Press, 1941. $1.75.

B. C. DAVISON. *The Japanese Earthquake of 1923*. London: Thos. Murby & Co., 1931.

B. ANGELO HEILPRIN. *Mont Pelee and the Tragedy of Martinique*. Lippincott, 1903. $3.00.

GLACIATION

C. W. H. HOBBS. *Characteristics of Existing Glaciers*. Macmillan, 1911. $3.75.

B. A. P. COLEMAN. *The Last Million Years*. Ed. G. F. KAY. University of Toronto Press, 1941. $3.50.

B. R. A. DALY. *The Changing World of the Ice Age*. Yale University Press, 1934. $5.00.

C. W. B. WRIGHT. *The Quaternary Ice Age*. 2d. ed. Macmillan, 1937. $6.00.

B. A. P. COLEMAN. *Ice Ages, Recent and Ancient*. Macmillan, 1926. $3.50.

B. C. A. COTTON. *Climatic Accidents in Landscape Making*. Macmillan, 1942. $4.75.

A. L. M. GOULD. *Cold*. Brewer Warren & Putnam, 1931. $3.50.

A. W. H. HOBBS. *Explorers of the Antarctic*. House of Field, Inc., 1941. $3.50.

A. W. CARLSON. *Greenland Lies North*. Macmillan, 1940. $3.00.

DESERTS

A. GAYLE PICKWELL. *Deserts*. McGraw-Hill, 1939. $3.50.

A. PAUL B. SEARS. *Deserts on the March*. University of Oklahoma Press, 1935. $2.50.

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[4] This special list was compiled in part from a more comprehensive "Bibliography of Military Geology and Geography" distributed free in mimeographed form by the Geological Society of America, 419 W. 117th Street, New York City. Supplementary translations by Professor Cloos of German works on that list are also available.

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REVIEWS

Late Paleozoic Pelecypods: Mytilacea. By NORMAN D. NEWELL. ("University of Kansas Publications, State Geological Survey of Kansas," Vol. X, Part II.) Lawrence, 1942. Pp. 80; figs. 22; pls. 15.

This is the second part of Dr. Newell's significant monograph on the Pennsylvanian and Permian pelecypods of the Mid-continent region. In Part I (Vol. X [1937]) the author considered the Pectinacea. In Part II, which concerns the Mytilacea, he describes in detail eleven genera and three subgenera of the superfamily; four genera, two subgenera, nineteen species and varieties are new.

The text, which is divided into two principal sections, the Introduction, and the "Systematic Paleontology," contains also a Preface by Raymond C. Moore, a Table of Contents, and an Index.

Embodied in the Introduction, which is important for all teachers and students of invertebrate paleontology, is a detailed discussion of the bionomics of living Mytilidae, which in turn is translated in terms of the Pennsylvanian and Permian occurrences. Following this is a discussion of evolutionary trends and a profusely illustrated, comprehensive presentation of shell morphology, which will be heartily welcomed by novice and veteran alike. Also included are charts showing the principal divisions of the American Pennsylvanian and Permian rocks plus the known stratigraphic range of the Late Paleozoic Mytilacea.

Outstanding in the second major section, or "Systematic Paleontology," is the consideration given to the variability and palingenesis of the Mytilacea through abundant use of frequency graphs, scattergrams, and form series. Dr. Newell emphasizes the importance of critical ontogenetic studies, which commonly reveal previously overlooked, polyphyletic conditions in the pelecypods. The section is concluded with the generic assignment of some foreign species, a list of references, and fifteen plates.

IRVING B. HAMILTON

Hydraulics. By GEORGE E. RUSSELL. 5th ed. New York: Henry Holt & Co., 1942. Pp. viii+468; figs. 238. $4.25.

This successful book, now in its fifth edition, is designed primarily for students and engineers whose professional work requires some knowledge of hydraulics. The first ten chapters have been completely re-written with recent trends of research and practice in mind. The chapters on hydraulic machinery have been brought up to date.

As was true of the previous editions, the fundamental principles of fluid flow are clearly presented and effectively illustrated by worked examples in the text. A generous number of interesting practical problems with answers are given at the end of each chapter.

Rather serious limitations have been placed upon the number of topics included and upon the extent of the analysis of the subject matter. Although the author carefully points out in the Preface that the text does not touch upon problems in aerodynamics, or contain discussions of problems of nonisothermal fluids, however, it is disappointing to the present reviewer to find nothing on the theory and use of the flow net and very little indeed on the transportation of sediments. Only a few remarks are made on modern theories of turbulence and the application of these theories to pipe friction.

MICHAEL FERENCE

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